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LABORATORY OCULOMETER

by John Merchant

Prepared by
HONEYWELL RADIATION CENTER
Lexington, Mass.
for Electronics Research Center

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By John Merchant

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INTRODUCTION

The Oculometer is an electro-optical device that measures the direction of pointing of the human eye. It is not attached to the subject, and operates with essentially invisible infra-red radiation.

The Oculometer can find application in cases where eye direction is to be measured with a minimum of interference to the subject -e.g.,

(a) psychological and physiological monitoring

(b) eye control -- that is the direct control of target acquisition/tracking systems by Oculometer signals defining the direction of pointing of operator's eye (Ref. 1).

The present Oculometer has been developed from the concept proven in an earlier breadboard unit (Ref. 1). The Oculometer consists of an optomechanical unit (Figure 1) and an electronics unit (Figure 2).

In operation, the eye is placed near a dichroic beam splitter at one end of the optomechanical unit. The eye is then illuminated by IR radiation from a source within the unit. An image of the eye is formed at the photocathode of the image dissector tube, also contained within the optomechanical unit. The electronics unit processes the video signal from the image dissector and generates scan signals form the image dissector, causing it to search for, acquire, and track the image of the eye that is

Figure 1 OPTOMECHANICAL UNIT

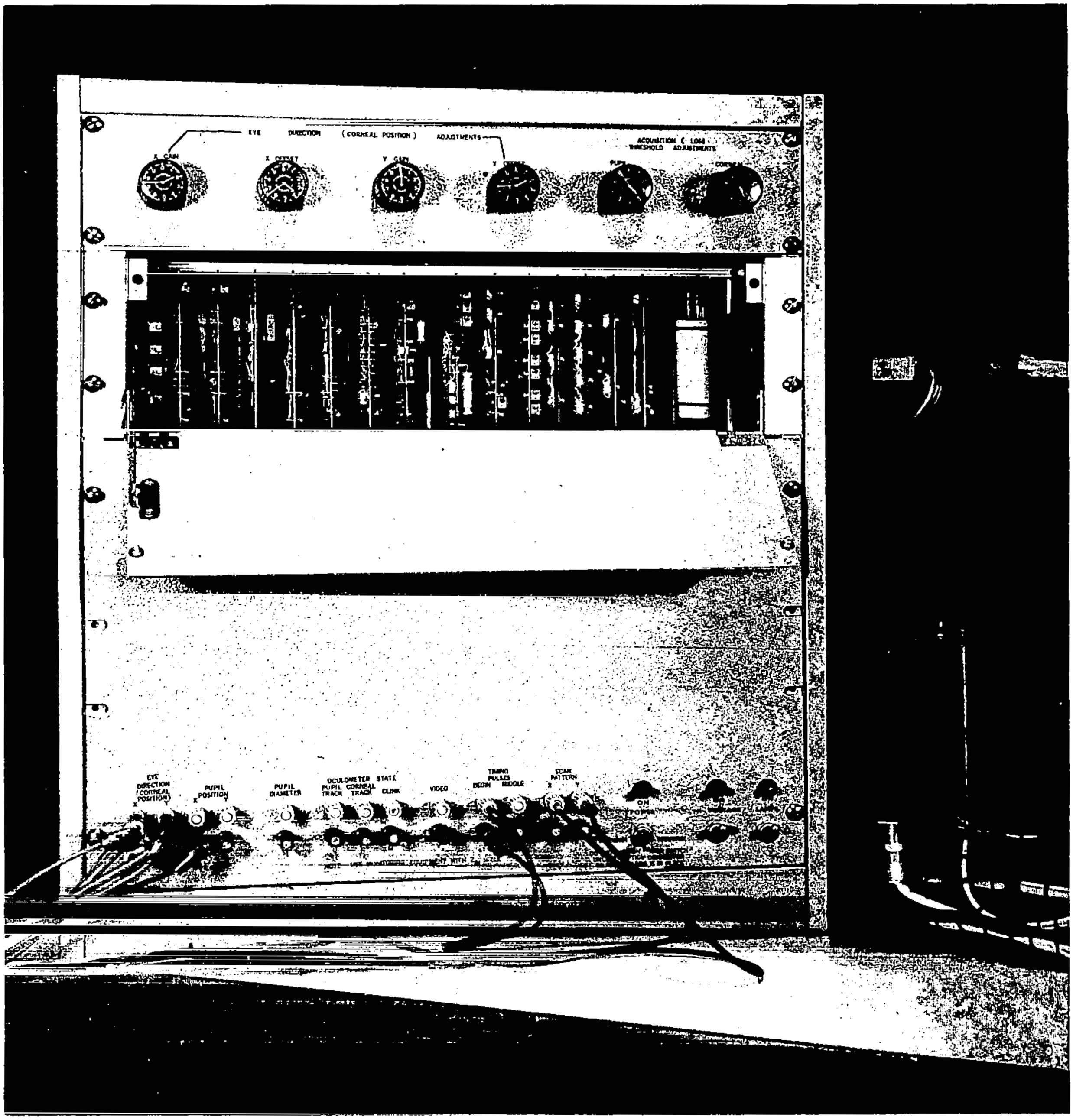


Figure 2 ELECTRONICS UNIT

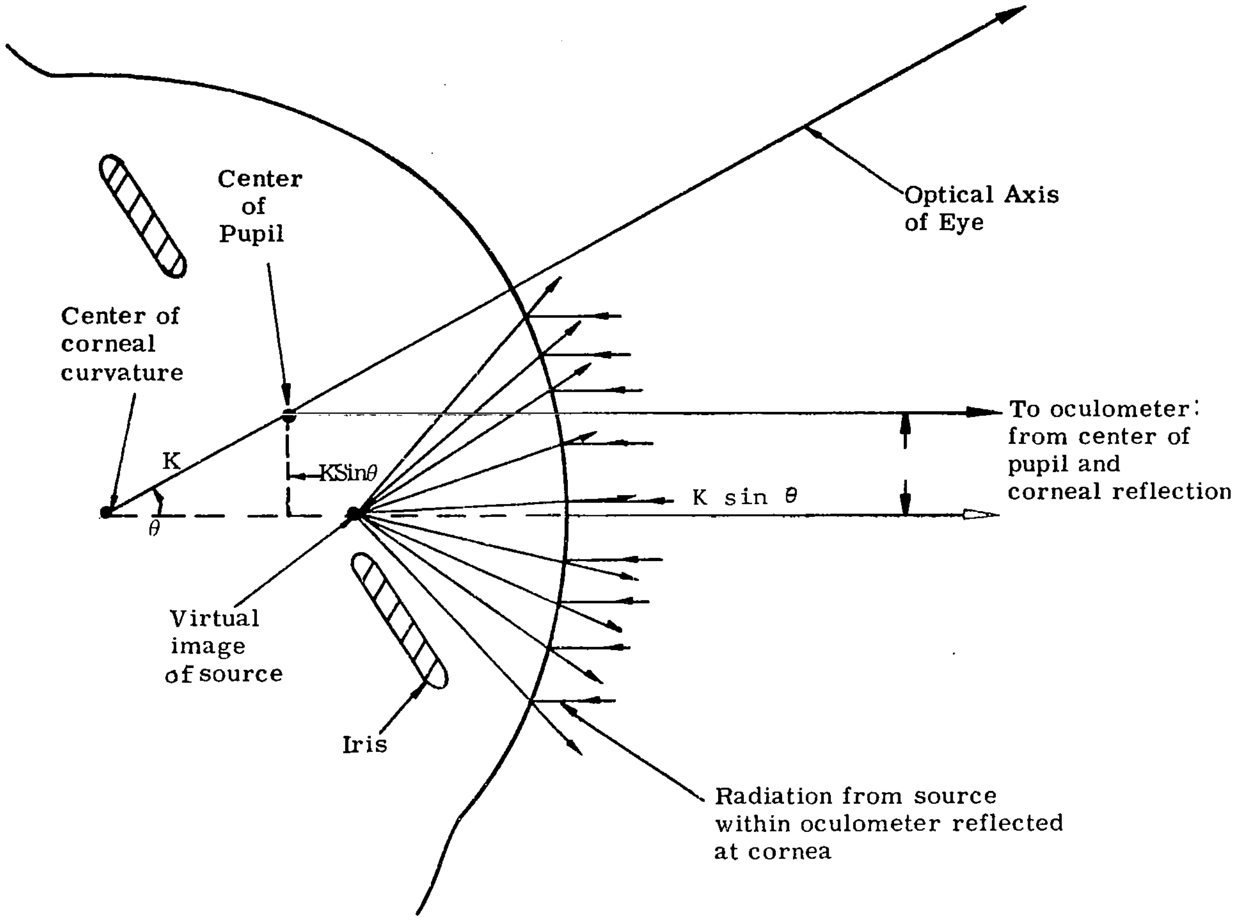
formed at the photocathode. Eye direction information is derived from this electronic tracking system. The system also provides a measure of pupil diameter and pupil position relative to the optical axis of the system.

In this document, the basic sensing principle, i.e., how eye direction is determined from the eye image, the optomechanical unit, the electronics system, and the performance of the device are described.

BASIC SENSING PRINCIPLE

The basic sensing principle of the Oculometer is that eye direction is defined by the position of a corneal reflection (of the radiation source within the Oculometer), relative to the center of the pupil.

More specifically, imagine that the eye is illuminated by a point source at infinity and is imaged onto a screen by an optical system whose point collection aperture is also at infinity, coincidentwith that of the illumination source. Some of the collimated radiation incident at the eye (Figure 3) is reflected at the cornea-axis surface (the reflection factor is about 2.5%). The rays reflected from the cornea appear to diverge from a point within the eye which is the virtual image of the source. (The corneal reflection of a finite bundle of collimated rays is actually an extended surface, not a point. However, this will not affect the basic result because, in the present case, the rays from an infinitely small incident bundle are reflected back to the collection aperture.) The actual ray reflected back from the cornea to the infinitely small collection aperture



Displacement of corneal reflection from center of pupil, K Sin θ, is proportional to the angular direction, θ, of the eye, and is independent of the position of the eye.

Figure 3 BASIC SENSING PRINCIPLE

(at infinity and coincident with the source) corresponds to that particular normal to the corneal surface which is parallel to the incident collimated rays.

As described in detail in the Mechanical Section, the pupil-iris boundary is illuminated in the Oculometer in such a way as to make this boundary clearly visible. By tracking this boundary, the center of the pupil can be determined. It can be assumed for the present purpose, therefore, that there is a luminous point at the center of the pupil. Because the aperture of the collection optics is assumed, for the moment, to be infinitely small and located at infinity, the only ray from this (imaginary) point at the center of the pupil, that will be collected, is the ray parallel to the incident collimated bundle. The displacement of the corneal reflection from the center of the pupil is (from Figure 3) $K \sin \theta$ where θ is the angle between the geometric axis of the eye and the direction of the incident collimated beam (which is a reference direction, the optical axis of the Oculometer) and K is a dimensional constant of the eye. Thus by measuring the displacement of the corneal reflection from the center of the pupil, in the eye image, a measure is obtained of the direction of the geometric axis of the eye.

Under the conditions stated, the displacement between the rays from the center of the pupil and from the corneal reflection is independent of the position of the eye in all three dimensions. That is, if the eye moves (with no rotation) in any direction, the displacement between the two rays is invariant. The displacement between the rays is solely a function of the angular direction of the eye.

In practice, the Oculometer employs a source and collection aperture of finite size. The finite size of the source aperture ($\approx 1.2°$ in the present case) results in a finite size of corneal reflection (about 0.003 in. diameter), and the finite size of the collection aperture ($\approx 1°$) results in a finite depth of focus, (about ±1 in. with a 0.02 in. sampling aperture at the eye).

The sensing techniques described define the direction of the geometrical axis of the eye, whereas it is the direction of the foveal axis that is usually of interest. The deviation between these axes is approximately 5-7 degrees.

Calibration of the device is required for each subject:

(a) to take out the 5 - 7 degree angle between the geometric and foveal axes.

(b) to allow for variations in the scale factor K (nominally about 0.003 inches per degree).

Angular rotations of the eyeball about the Oculometer reference (z) axis will cause errors due to the deviation between the foveal and geometrical axes of the eye (about 1 degree error for 10 degree roll angles of the eye). Angular rotations of the eye about the z-axis may occur not only with head roll but also in the normal course of eye motions. To the extent that these eye motions are in accord with Listing's Law (Ref 2) they will not cause errors per se, but will affect the calibration (linearity, crosstalk) of the device. According to Reference 3, deviations from Listing's Law are small (1/4 degree for eye rotations of the magnitude incurred on normal vision). This implies that errors due to unexpected roll of the eye will, in normal circumstances, be very small (e.g., 1/40 degree).

OPTOMECHANICAL

The following is a description of the mechanical features of the Oculometer and how they operate.

Illumination Technique

In the prior breadboard system (Ref. 1), the eye was illuminated by visible radiation in such a way as to show the iris as relatively bright and the pupil relatively dark.

In the present system, a new, and improved illumination technique is used in which the eye is irradiated with almost invisible IR radiation to show the pupil as a bright uniform disc (together with a small highlight corneal reflection) against a virtually black background.

The new illumination technique is illustrated in principle in Figure 4. Light is projected from a small light source onto the retina via a beam splitter in front of the eye. An image of the light source is formed on the retina and a fraction of the incident radiation is scattered back from this point on the retina. Some of the scattered rays are collected by the eye lens and then refracted in such a way that when emerging from the eye, the rays retrace, exactly, the path of the incident rays from the light source. The emergent rays are passed through the beam splitter to a lens, which is located at the virtual image of the light source in the beam splitter. Since the emergent rays are focussed back, by the eye lens, to the light source, the emergent rays passing through the beam splitter converge to a small area at the lens, corresponding to the small area of the

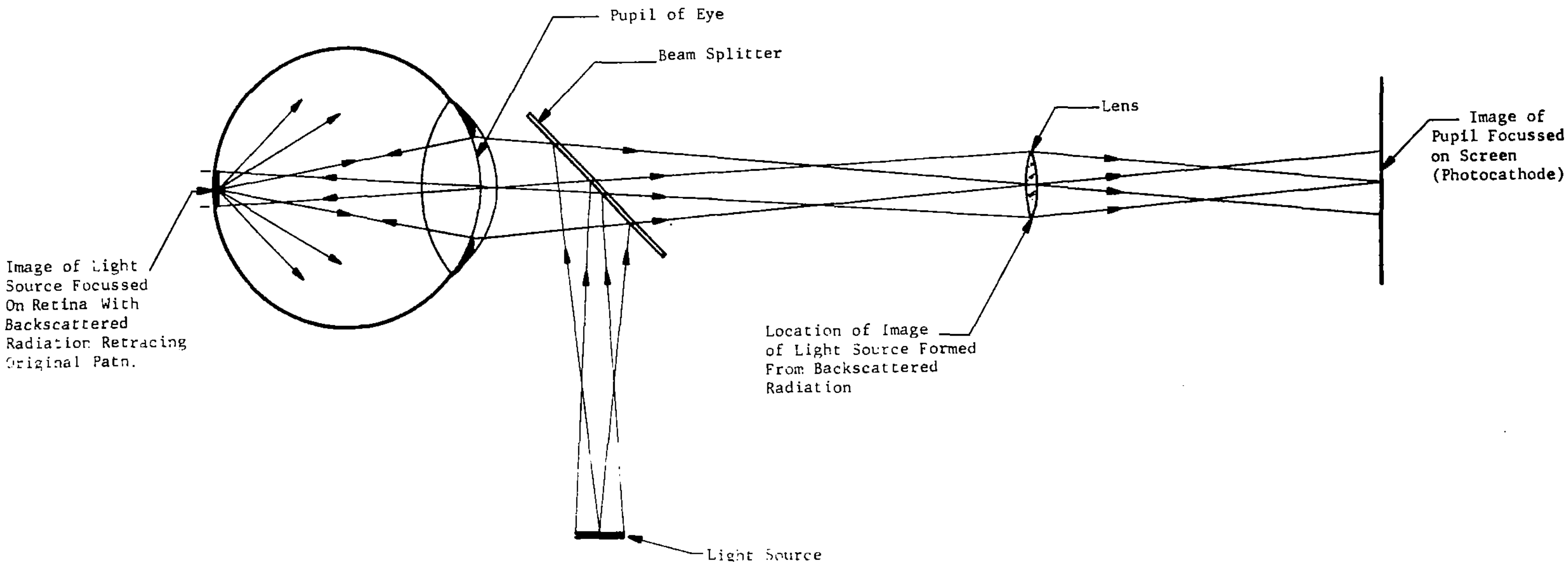


Figure 4 NEW RETINAL METHOD OF PUPIL/IRIS BOUNDARY ILLUMINATION

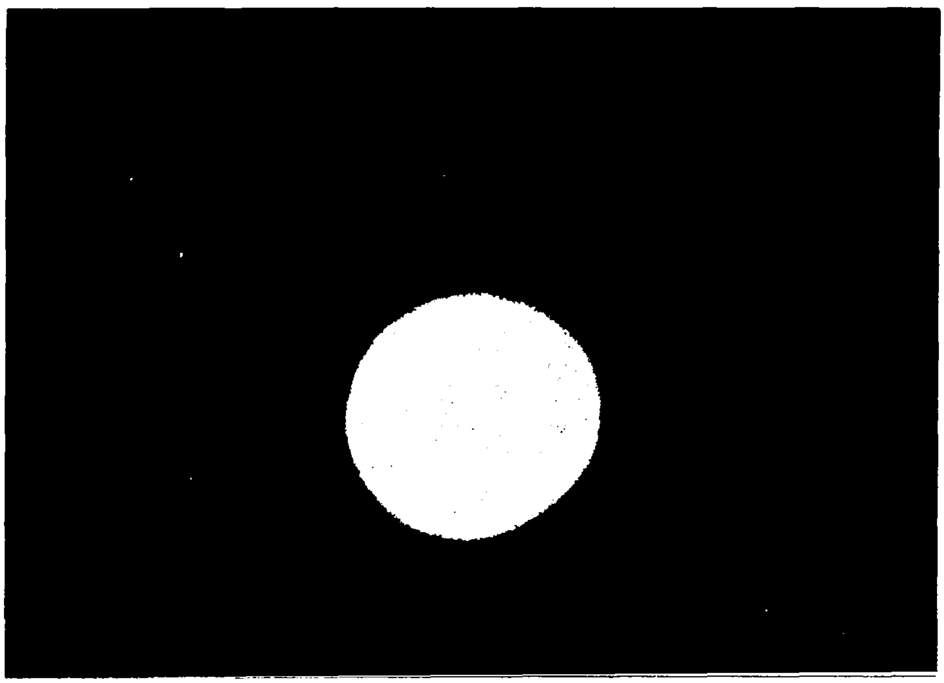


Figure 6 PUPIL AREA OF THE EYE

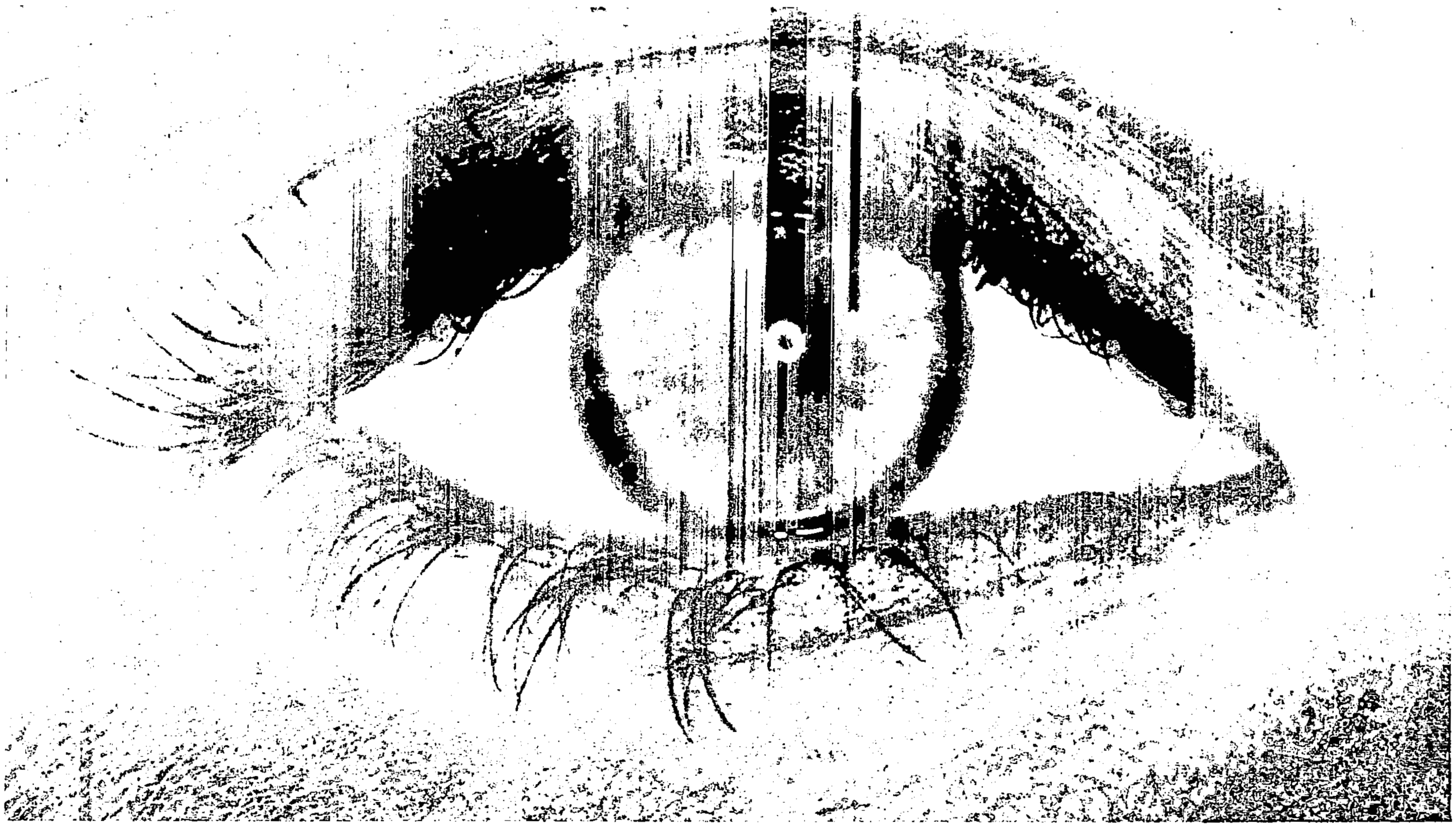


Figure 7 PREVIOUS PUPIL/IRIS ILLUMINATION TECHNIQUES

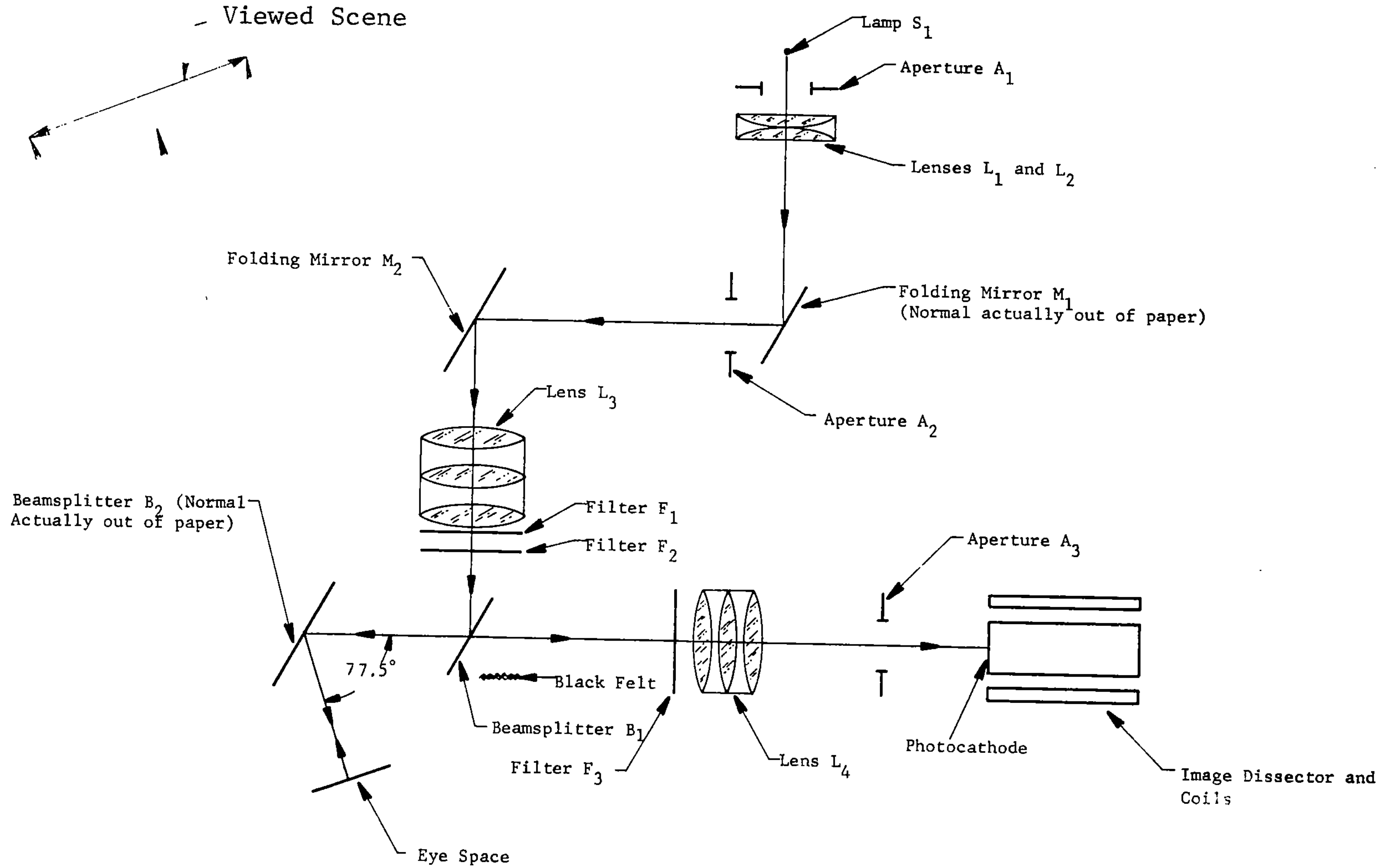


Figure 8 OCULOMETER OPTICAL SYSTEM (Explanatory Notes in Table 1)

TABLE 1

EXPLANATORY NOTES ON FIGURE 8

1. Plano-convex lenses L_1 and L_2 image lamp filaments S_1 onto aperture A_2 with magnification of approximately 3:1. Aperture A_1 stops down lenses L_1 and L_2.

2. Lens L_3 images aperture A_2 at infinity.

3. Lens L_4 images eye space onto photocathode with approximately 5:6 magnification.

4. Lens L_4 images aperture A_3 at infinity.

5. The image of A_2 reflected by beamsplitter B_1 is coincident with image of A_3 formed by Lens L_4.

6. Beamsplitter B_1 is 60% transmitting, 40% reflecting, in the 0.80 to 0.95 micron region.

7. Beamsplitter B_2 is substantially reflecting in 0.80 to 0.92 micron region, it is substantially transmitting in visible region.

8. F_2 and F_3 are Kodak wratten No. 87 filters, they attenuate the visible radiation.

9. F_1 is a Corning No. 7-69 filter, it attenuates visible radiation and infrared above 1.0 microns.

10. The strip of black felt prevents radiation from filament S_1 from being undesirably backscattered into the collection optics (L_4).

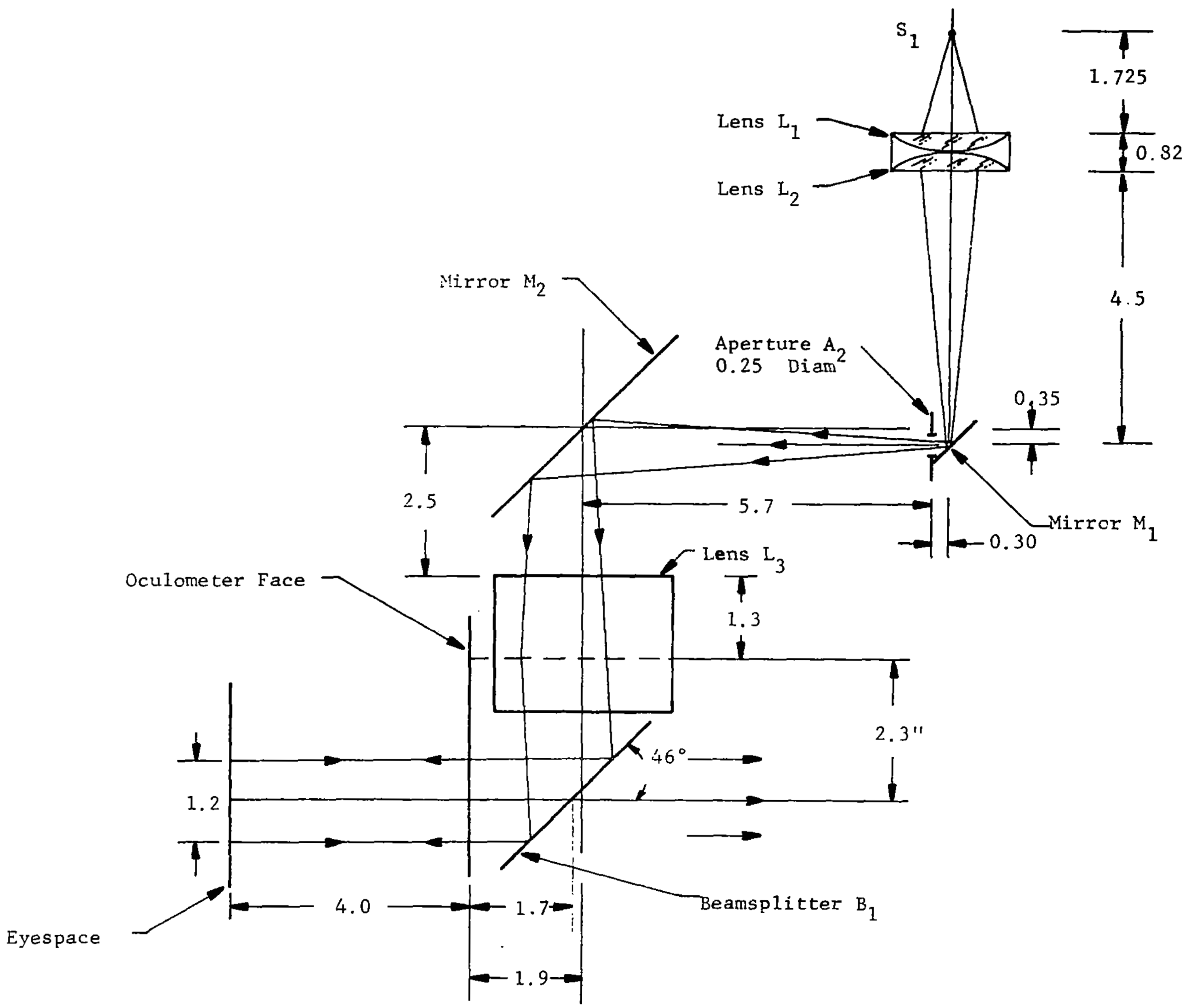
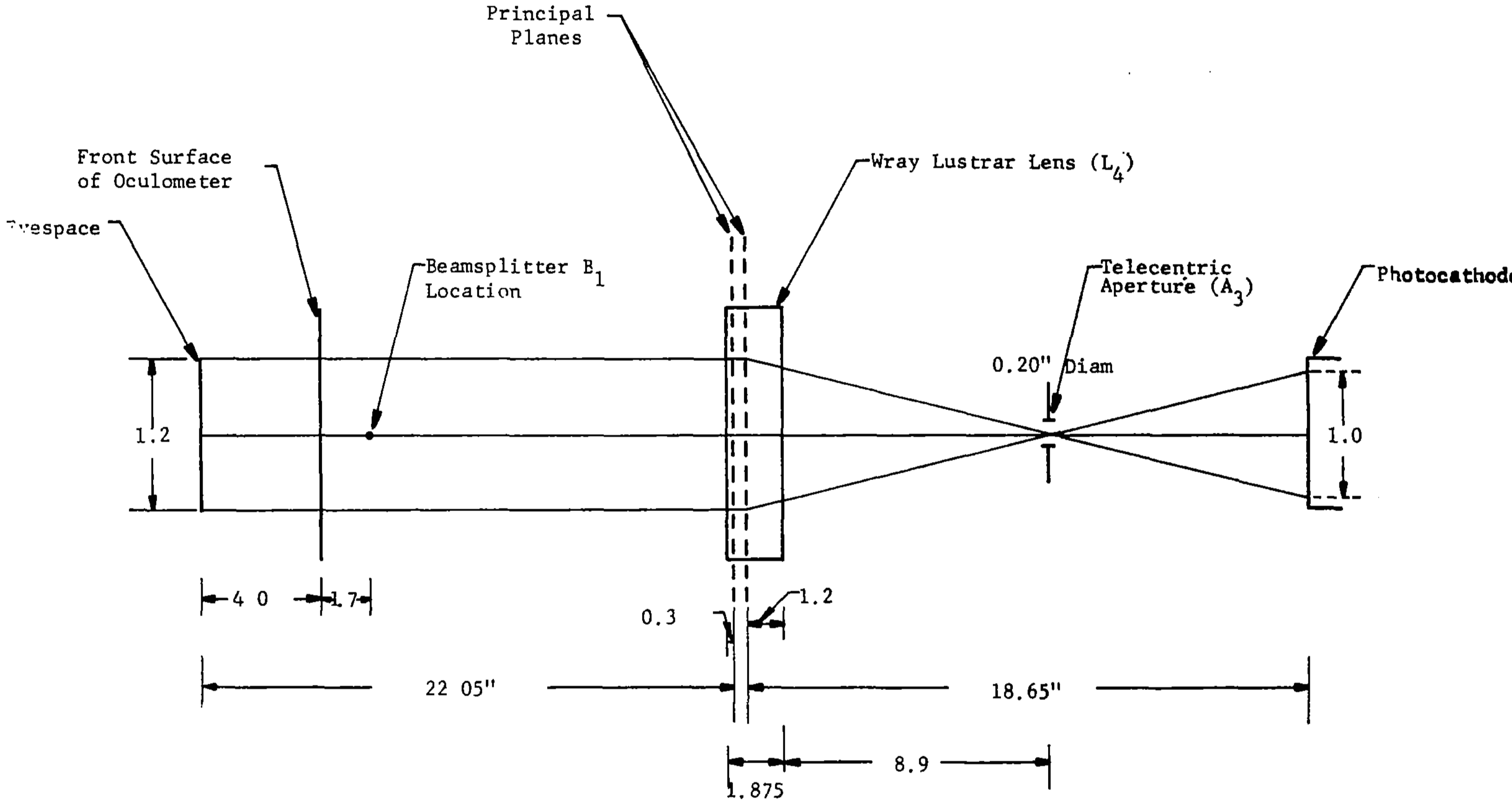


Figure 9 ILLUMINATION OPTICS



Scales: Horizontal - 1/4 x Vertical

Figure 10 COLLECTION OPTICS

dimensions). Radiation from a tungsten filament lamp is collected by an f/1.5 double plano convex lens system and an enlarged image of the filament is formed at the illumination aperture. The illumination aperture itself is at the focal plane of the main illumination lens and appears, to the eye, therefore, to be at infinity.

The cone angle of the rays at the illumination aperture is sufficient so that this aperture fully illuminates the 1.2 inch diameter region of the eye space provided. (The eye space is the space where the eye may be placed for normal operation of the device).

The illumination rays are directed onto the eye by reflection at the neutral and dichroic beam splitters. The eye views normally by transmission through the dichroic beam splitter. The eye is imaged onto the photocathode by rays reflected from the dichroic beam splitter and transmitted by the neutral beam splitter. The rays from the eye are collected by the collection aperture which is at the focal plane of the imaging lens. This aperture, also, appears to the eye to be at infinity and is arranged to be coincident (at infinity) with the illumination aperture. The distances from the eye to the imaging lens, and from the imaging lens to the photocathode are such that the eye space is imaged onto the photocathode with a magnification of 0.83X.

An image of the eye (as in Figure 11) is formed at the plane of the image dissector photocathode. The intensity of this image is analyzed in Appendix B as a function of the source brightness--a safe level of radiation at the eye and the optical system of the Oculometer.

Figure 11 EYE IMAGE

Electro-Optical Sensor

An ITT F4011 $1\frac{1}{2}$ in. vidissector (image dissector) is used as the basic electro-optical sensor, with an F4513 deflection coil and F4506 focus coil (Figure 12 and 13). The operating voltages are listed in Table 2. The F4011 has an S1 photocathode with a nominal quantum efficiency of 0.3% at the Oculometer operating band.

Electrons are emitted from the photocathode in proportion to the incident IR radiation. These electrons are accelerated by a 600 volt field towards an aperture plate having a central 0.017 in. diameter circular aperture. The electrons are magnetically focussed onto this plate to form an electron image of the eye.

The electron image at the aperture plate can be deflected in two dimensions by magnetic fields applied by the deflection coil. In this way the 0.017 in. clear aperture can be laid over any part of the eye image. The optical magnification is such that the image dissector aperture diameter, referred to the eye, is 0.02 in. The electrons falling onto this clear aperture pass through to the multiplier section of the tube having a gain of about 3×10^6. The output current from the image dissector is thus proportional to the average intensity of that region of the optical image at the photocathode corresponding to the 0.017 in. aperture. The position of this region in turn, is determined by the currents flowing in the x and y deflection coils.

NOTE: All dimensions in inches

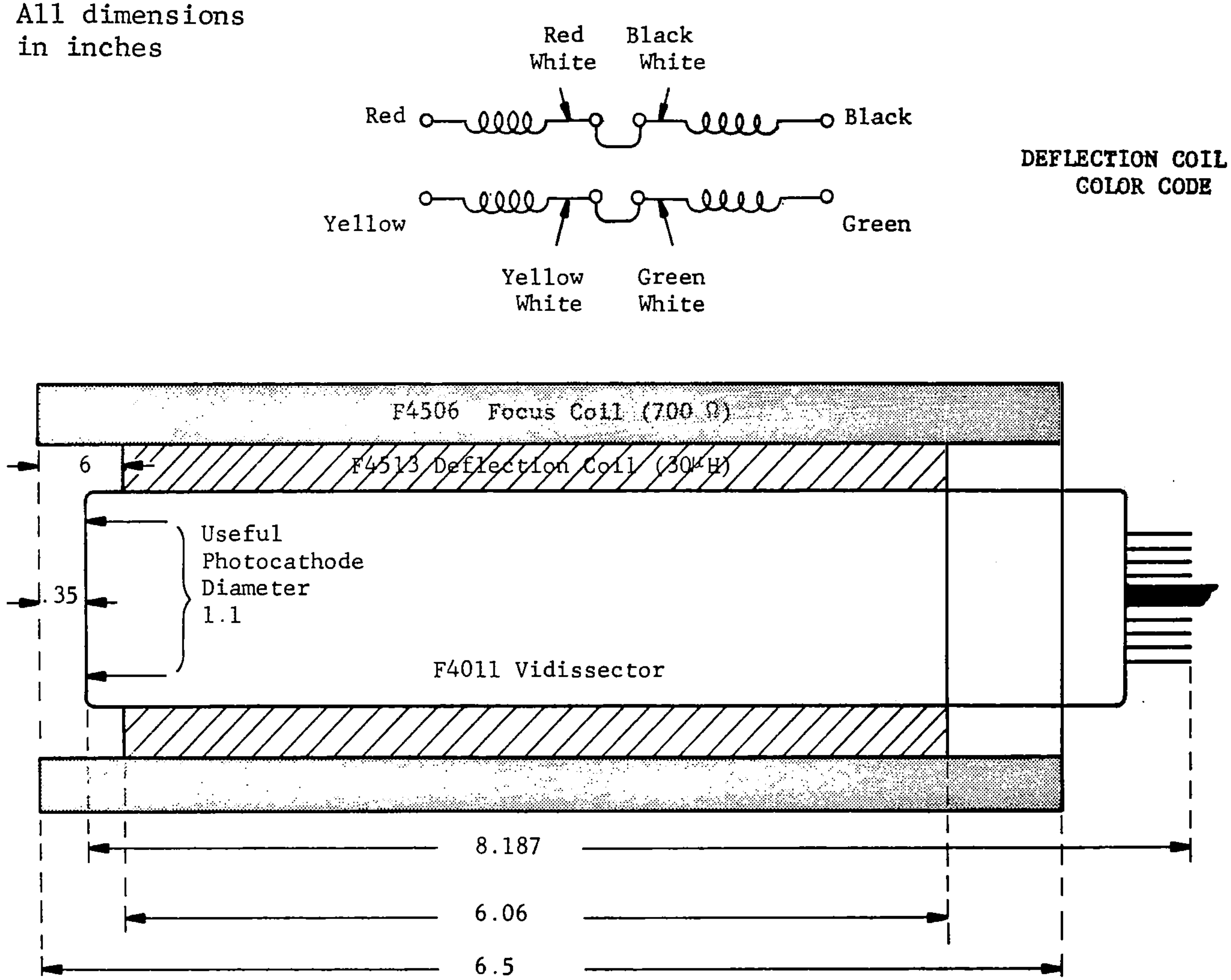
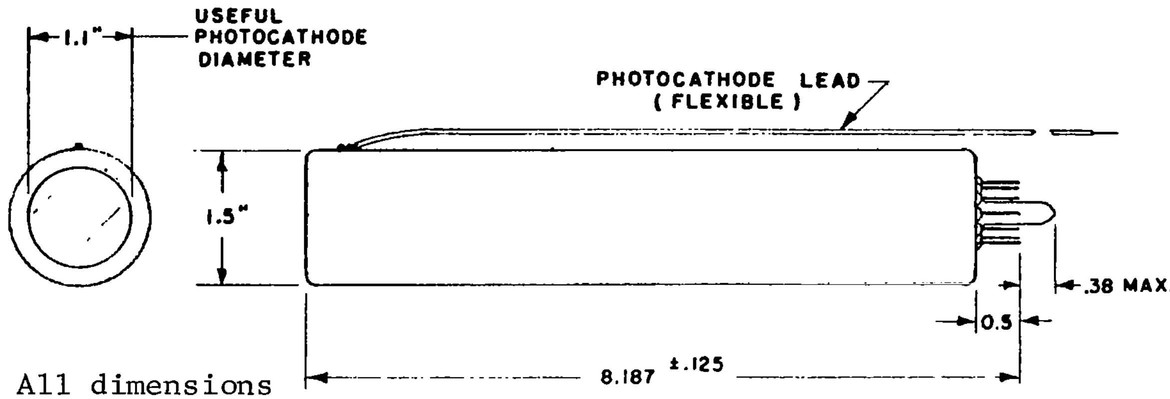


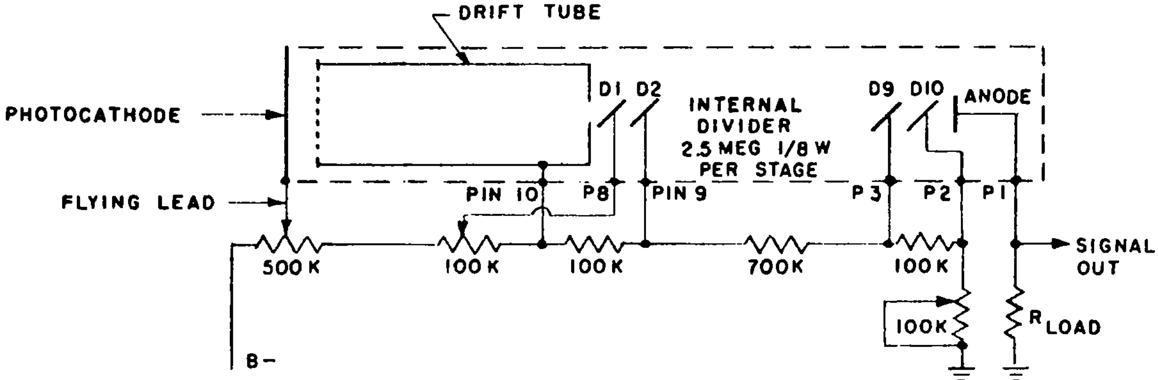
Figure 12 IMAGE DISSECTOR AND COILS

OUTLINE DRAWING

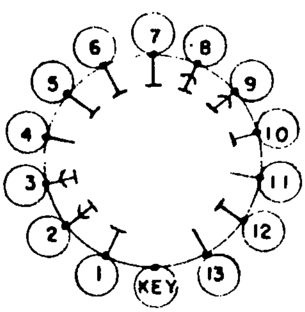


NOTE: All dimensions in inches

ELECTRICAL SCHEMATIC



PIN CONNECTIONS



Pin	Element
1	Anode
2	Dynode 10
3	Dynode 9
4	NC
5	Internal Connection
6	Internal Connection
7	Internal Connection
8	Dynode 1
9	Dynode 2
10	Drift Tube
11	Internal Connection
12	Shield
13	Internal Connection

Figure 13 IMAGE DISSECTOR CONNECTIONS

TABLE 2

IMAGE DISSECTOR OPERATING VOLTAGES

CATHODE - DRIFT TUBE	600V
CATHODE - D1	575V
CATHODE - D2	672V
DRIFT TUBE - GROUND	1400V
D1 - GROUND	1425V
D2 - GROUND	1328V
D10 - GROUND	105V
OVERALL	2000V

ELECTRONIC SYSTEM

The following is a description of the Electronics of the Oculometer and how they function.

Overall System

The electronics system (Figure 14) can be in any one of the following states

Pupil Track/Corneal Track (Q = 1, R = 1)
Pupil Track/Corneal Search (Q = 1, R = 0)
Pupil Search (Q = 0)

The particular state that the Oculometer is in is determined by the corneal and pupil state sensors (cards 7 and 8). These sensors process the signal output from the image dissector and set the logic signals R and Q at either "1" or "0".

In the pupil track/corneal track mode the deflection coils apply a constant circular scan pattern (Figure 15) together with pupil position and corneal position signals. The total effect is as illustrated in Figure 16. The top portion of the circular scan is not used for pupil tracking in order to avoid errors due to obscuration of the pupil by the upper eye-lid and lashes.

The image dissector output signal is processed initially on card 9 to generate video signals for each of the five tracking loops (pupil diameter, pupil position (x and y) and corneal position (x and y)). The image dissector scan signals are assembled from a fixed circular scan pattern together with the

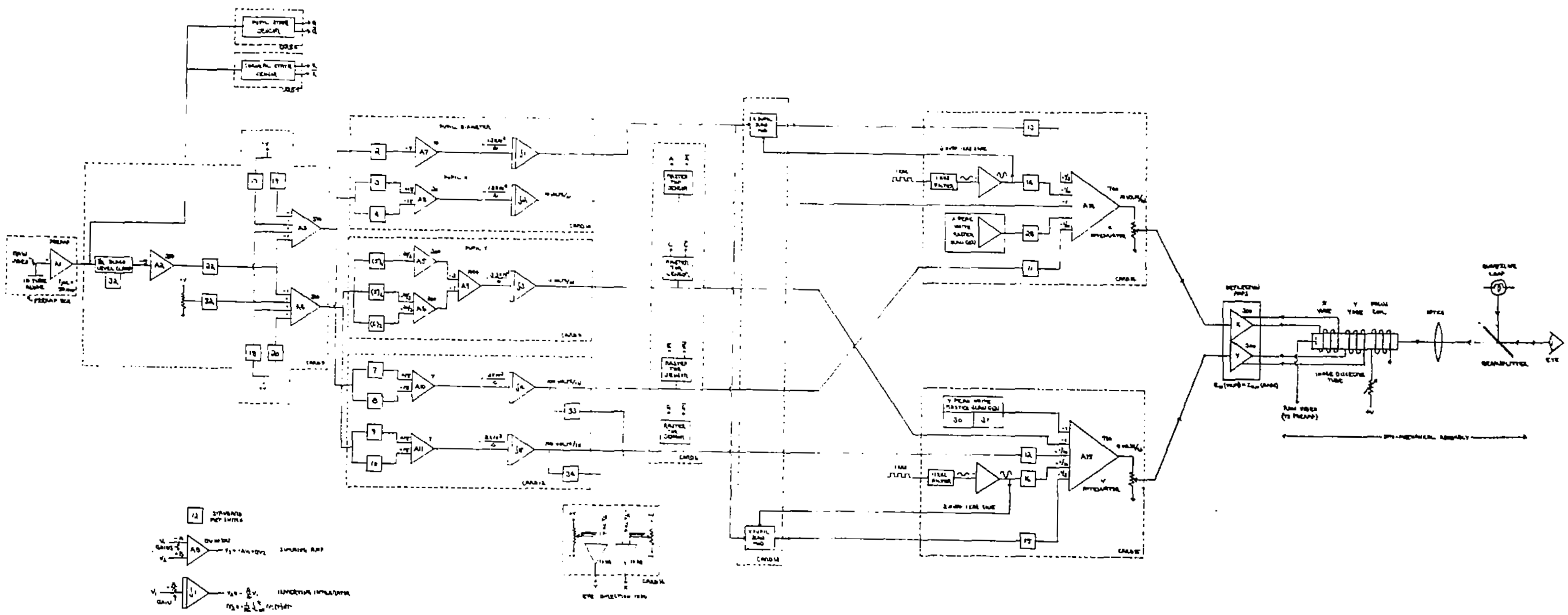


Figure 14 ELECTRONIC SYSTEM

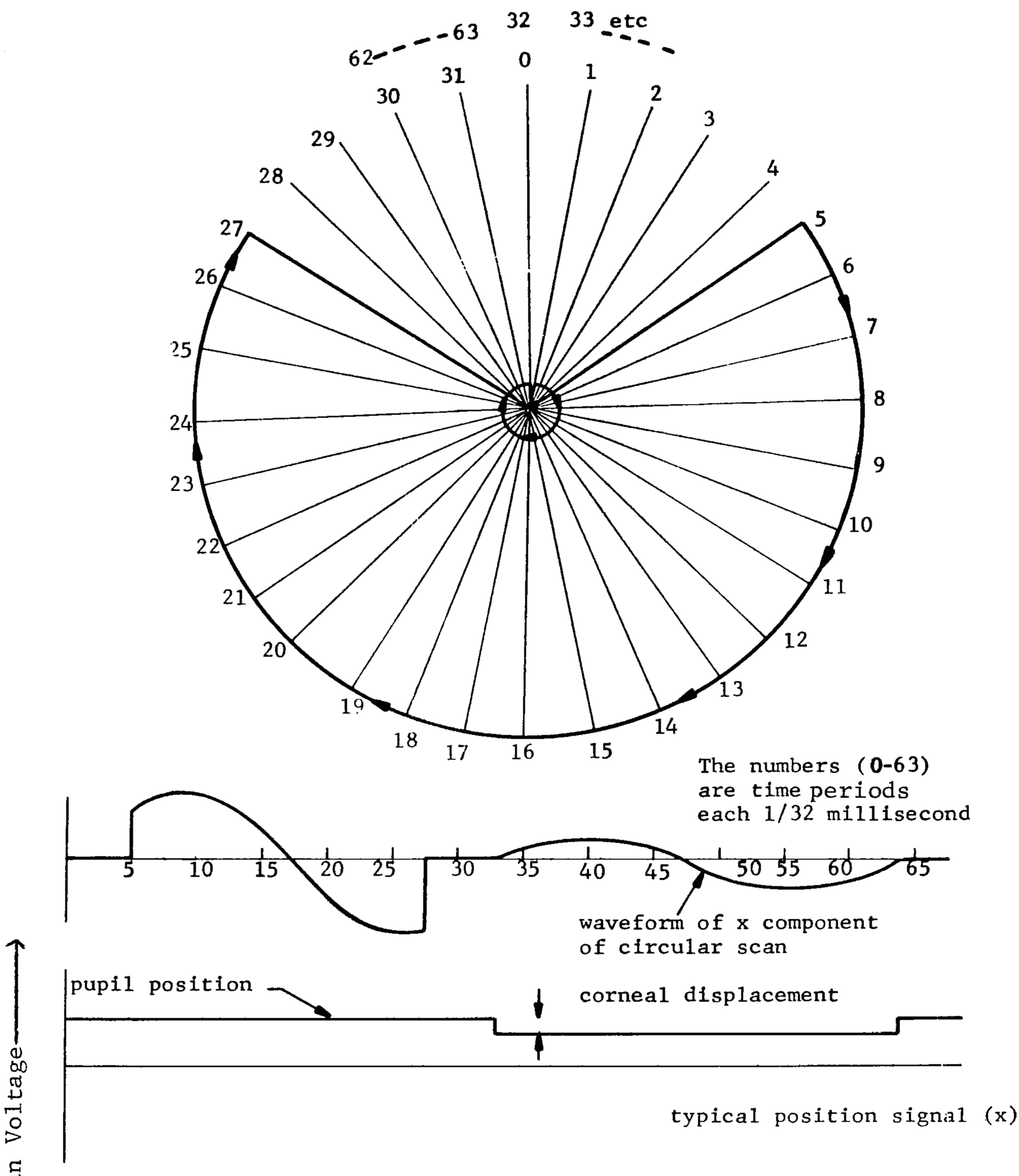
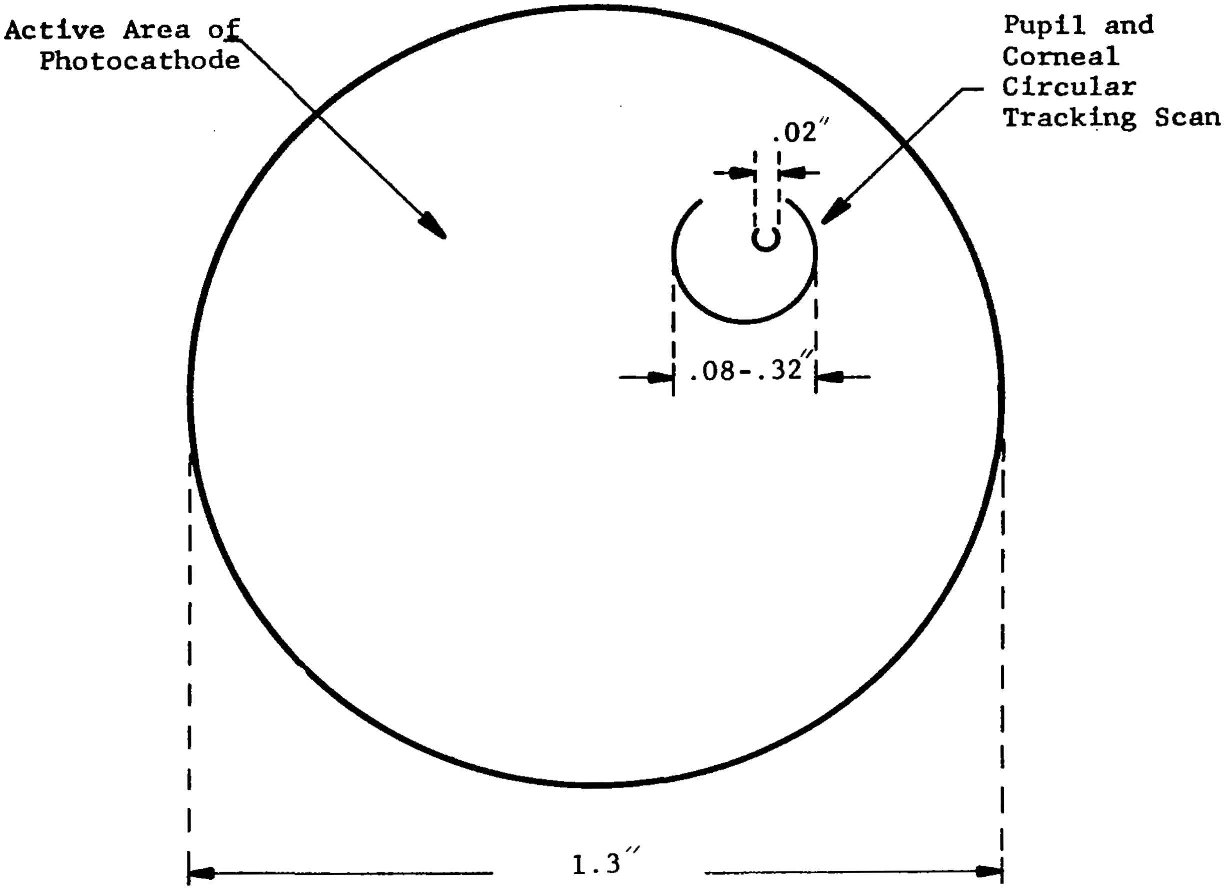


Figure 15 BASIC CIRCULAR SCAN



(All dimensions are in inches and are referred to the Eye Space)

Figure 16 PUPIL AND CORNEAL TRACKING SCANS computed scan position signals on cards 14 (x) and 15 (y). These deflection signals are applied to individual CELCO DA-PP 2B deflection coil amplifiers (which are located on the main electronics chassis alongside the power supplies).

A very simplified block schematic diagram of the Oculometer tracking system is shown in Figure 17.

The pupil and corneal circular tracking scans are derived from a 1 kHz sinusoidal source, which in turn is derived from a master clock system. The video output from the image dissector is applied to pupil diameter, pupil position, and corneal position demodulators. The output from these demodulators is a signal proportional to the instantaneous scan position error, and is applied to the associated integrators. The integrator outputs control pupil scan diameter, pupil scan position and corneal scan position (relative to the center of the pupil). The various position and scan signals are assembled and applied to the image dissector deflection coil.

Let it be assumed that the scan system is exactly aligned with the appropriate eye detail. The output from all the demodulators will be zero and the integrator outputs will not change. If the eye displaces, then the video output from the image dissector will change. The demodulators will generate, from this video, an appropriate error signal proportional to the existing scan position error. This error signal will cause the associated integrator outputs to change in such a way as to correct the existing error in scan position. When the error has been corrected, all the error signals from the demodulators will be zero, the integrator outputs will not change, and the scan will remain correctly positioned over the eye detail.

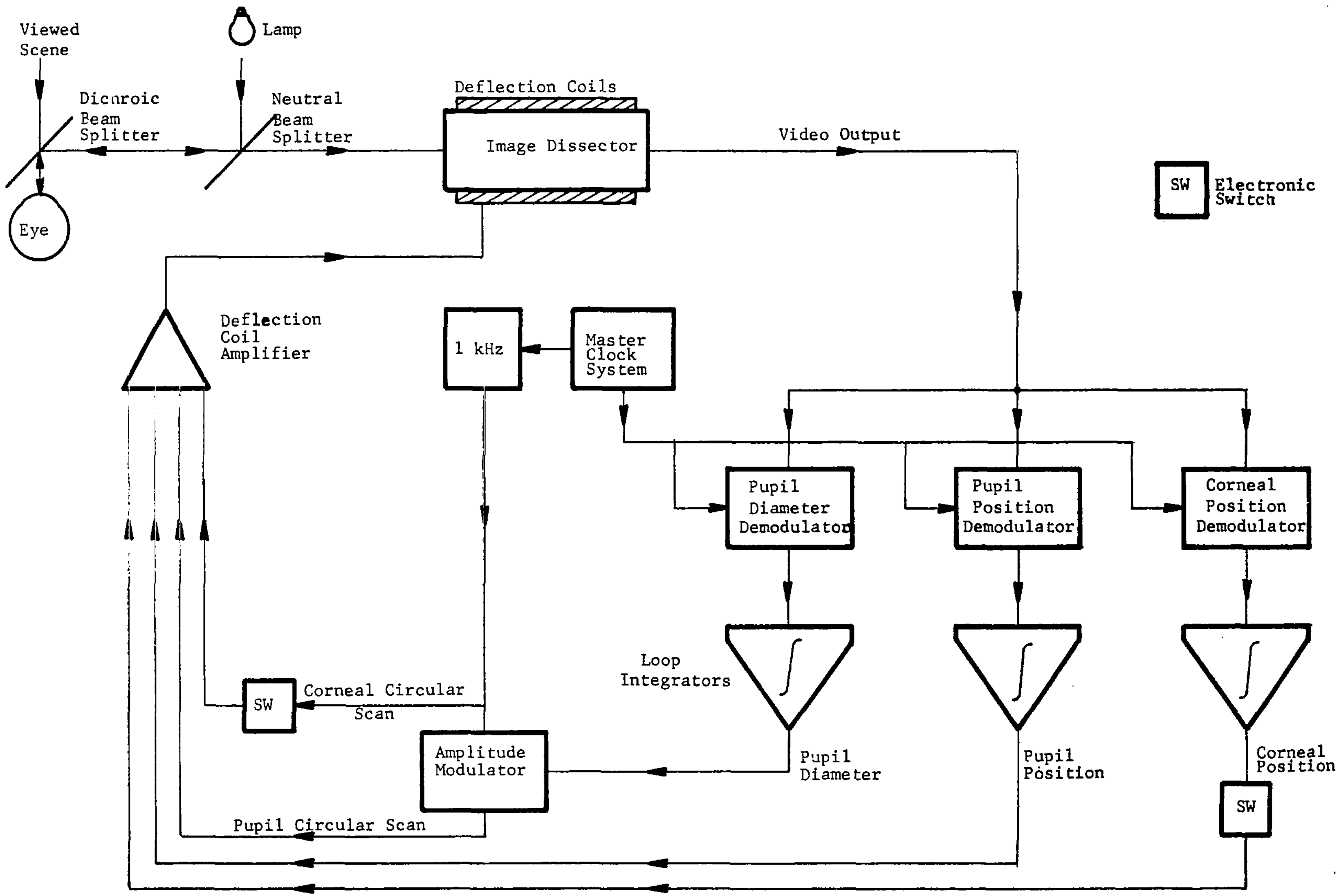


Figure 17 OCULOMETER TRACKING SYSTEM

The basic scan period of the Oculometer is 2 milliseconds. That is, the scan pattern shown in Figures 15 and 16 has a period of 2 milliseconds (derived from a 256 kHz crystal oscillator on card 1). This period may be regarded as consisting of 64 time periods each 1/32 millisecond long. The pupil tracking scan exists from time periods 5 to 27 and the corneal tracking scan from time periods 32 and 64 (See Figure 15).

The video from the image dissector is processed to yield pupil and corneal scan position error signals. As illustrated in Figure 18 this is accomplished by (effectively) multiplying the video with appropriate demodulation functions which are synchronized with the scan pattern. The pupil and corneal tracking scans are shown, in the upper part of Figure 18, slightly misaligned from the pupil and corneal reflection. Because of this misalignment, the image dissector signal output will fluctuate as the scanning aperture (of the image dissector) is made, by the circular scan, to fall over alternately lighter and darker positions of the image. The resulting video signal is illustrated schematically as the first function shown in Figure 18. The corneal and pupil x and y demodulation functions are shown next in Figure 18. In the Oculometer the video is multiplied by these functions to yield scan position error signals. The x demodulated video is illustrated at the bottom of Figure 18. It can be seen from Figure 18 that if the scan is perfectly aligned with the pupil and corneal reflection there will be no 1 kHz modulation superimposed on the video and the average value of each of the components (pupil x and y, corneal x and y) of the demodulated video will then be zero.

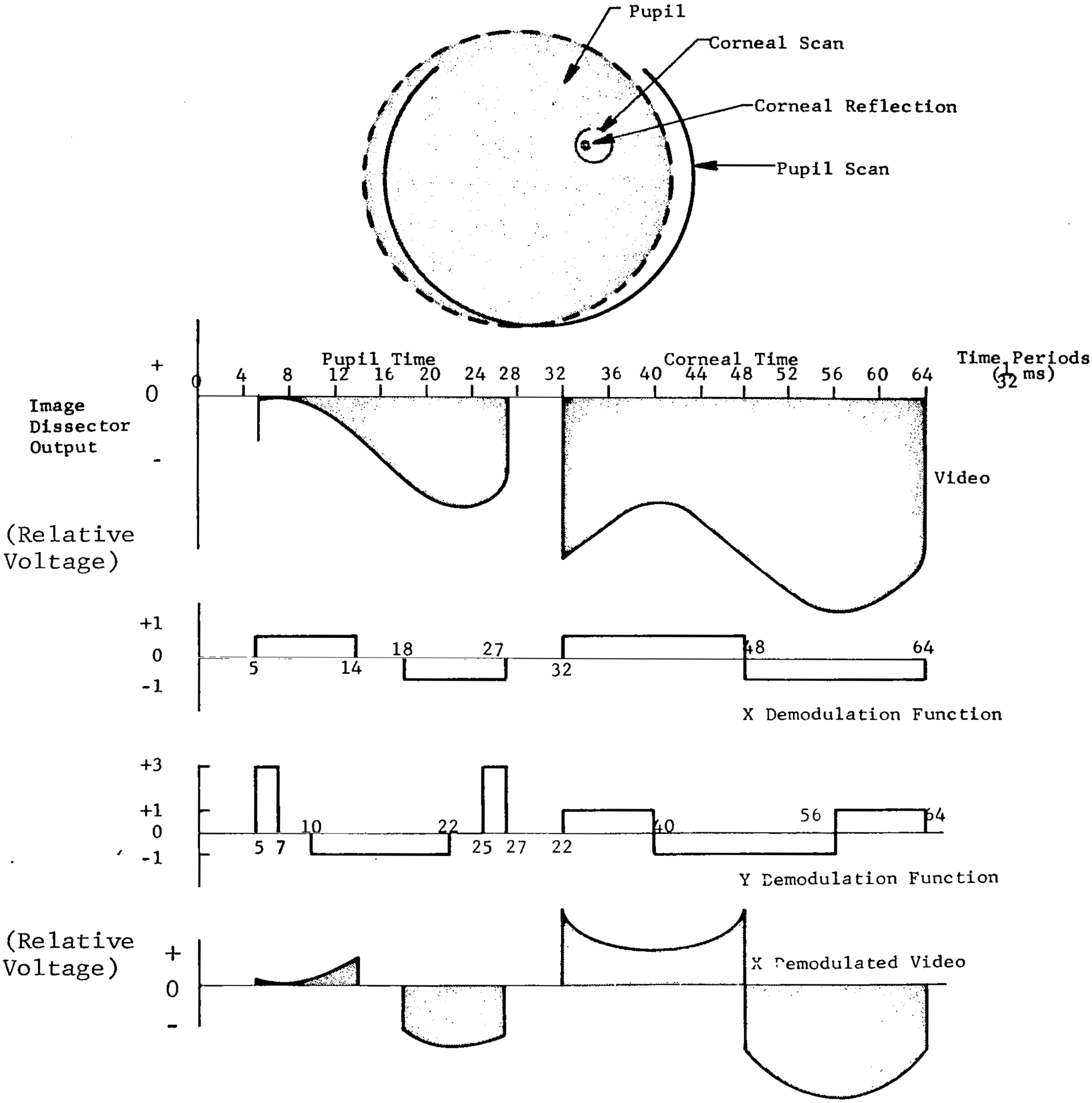


Figure 18 POSITION DEMODULATION FUNCTIONS

It also can be seen from the video illustrated in Figure 18 that any 1 kHz modulation present in the image dissector output is superimposed on a dc level. In pupil time this dc level may be termed 'half peak white' — where 'peak white' is the output level that would result if the scanning aperture were wholly within the pupil (Figure 19). The video level is only one half of peak white in pupil time because, nominally, the scanning aperture is made to sit half way over the pupil boundary when the scan is optimally aligned with the pupil.

In the Oculometer the two dc components — half peak white in pupil time, and peak white plus corneal signal in corneal time — are removed. The half peak white level is removed by a clamp. The peak white plus corneal signal is removed partially by this clamp and also by the injection of an appropriate dc level (Figure 14). Both these functions are performed on card 9, and are explained in more detail in the description, below, of that card.

The video, clamped to half peak white, is illustrated in Figure 20 for the case when the pupil scan diameter is too large (i.e., greater than that of the eye pupil) and also for the case when the scan diameter is correct. In the latter case it can be seen, from Figure 20, that the average value of the demodulated video is zero — yielding a zero error signal. In the case when the scan diameter is too large the clamped video is above zero and the demodulated video then has a resultant average value.

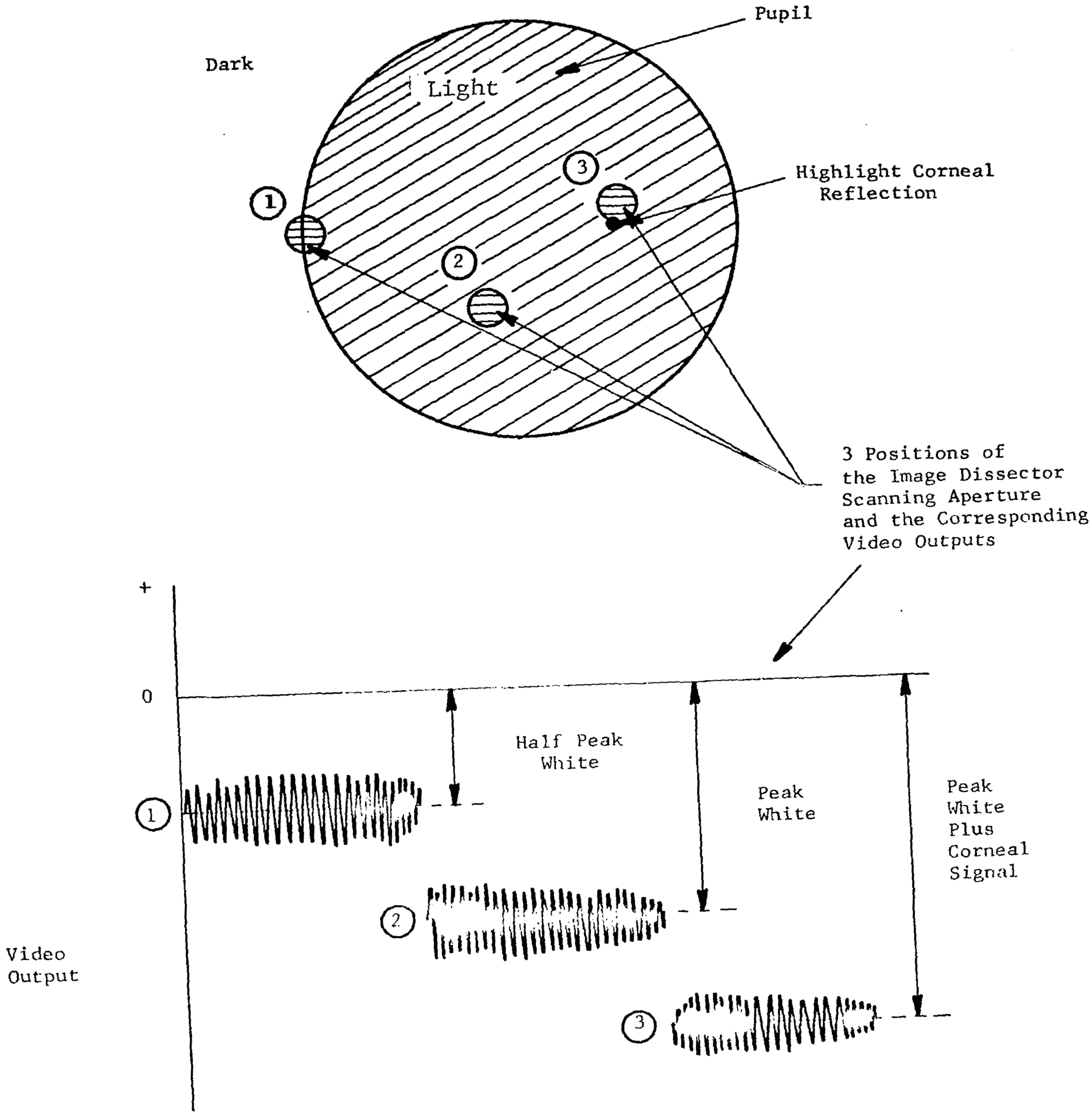


Figure 19 VIDEO OUTPUT LEVELS

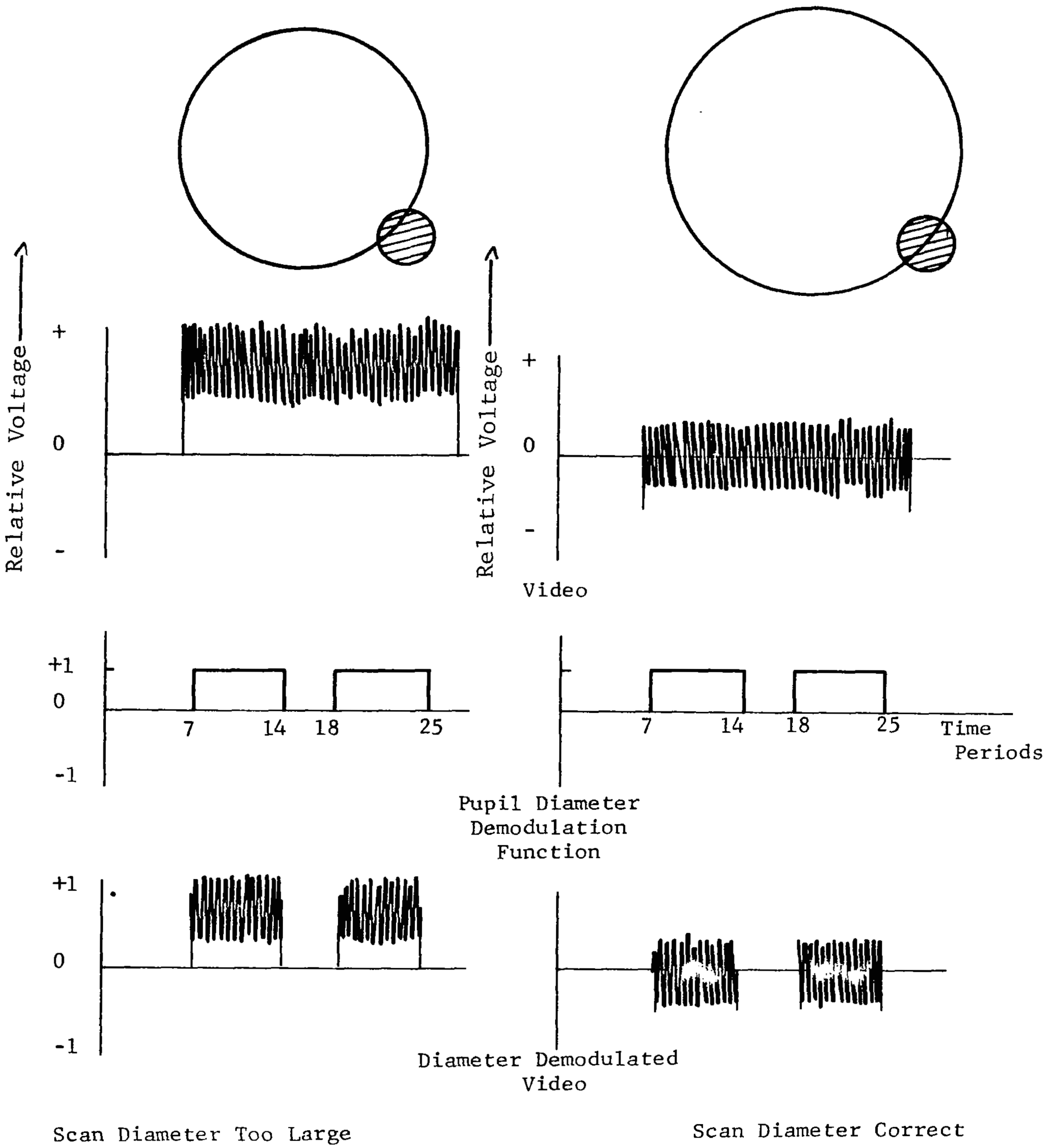


Figure 20 PUPIL DIAMETER DEMODULATION

The various loop error voltages are generated (as shown in Figure 14 by:

Amplifier A7 on card 9 for pupil diameter
Amplifier A8 on card 9 for pupil x position
Amplifier A9 on card 10 for pupil y position
Amplifier A10 on card 11 for corneal x position
Amplifier A11 on card 11 for corneal y position

In each case the error voltage is applied to an integrator.

The dynamic response function of all five loops is of the same form. For the i^{th} loop let the scale factor of the demodulator output be V_i volts per inch error. Let the scale factor of the integrator output be W_i volts per inch. Let the time constant of the integrator be τ_i (Figure 21). Let μ be the actual output of the integrator (in volts) and μ_o the value that corresponds to the position of the eye.

$$\text{Then, scan error} = \frac{\mu - \mu_o}{W_i} \text{ volts}$$

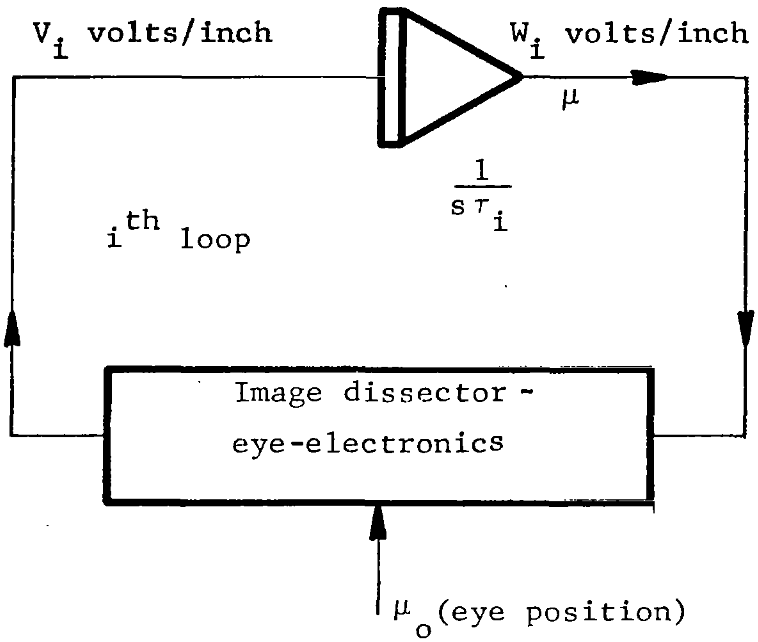
$$\therefore \text{Feedback error voltage} = -V_i \left(\frac{\mu - \mu_o}{W_i}\right) \text{ volts}$$

$$\therefore \mu = -\frac{(\mu - \mu_o)}{W_i \; s} \frac{V_i}{\tau_i}$$

$$\therefore \mu = \frac{\mu_o}{\frac{s\tau_i W_i}{V_i} + 1}$$

Thus the loop response is of a simple low pass RC filter with a time constant given by:

$$\text{Loop time constant} = \frac{\tau_i W_i}{V_i}$$



$$\mu = \frac{\mu_o}{1 + \frac{\tau_i W_i S}{V_i}}$$

$$\text{Loop Time Constant} = \frac{W_i \tau_i}{V_i}$$

Figure 21 GENERALIZED LOOP RESPONSE FUNCTIONS

The output of the pupil diameter integrator ($\int 1$ on card 10) is applied to the x and y pupil scan modulators, both located on card 13. The level of two quadrature 1 kHz sinusoids is made directly proportional to this input from the pupil diameter integrator. These two 1 kHz sinusoids are then applied to the x and y scan summing amplifiers (A14 on card 14, A15 on card 15) to generate the pupil circular scan, the diameter of which is controlled by the output of integrator 1 on card 10.

The outputs of the pupil position integrators ($\int 2$ on card 10, $\int 3$ on card 11) and of the corneal position integrators ($\int 4$, $\int 5$ on card 12) are applied to the scan summing amplifiers as shown in Figure 14.

In the pupil search mode the circular scan is suppressed and the 5 tracking loops are disabled. Fixed dc voltages are applied to the x and y pupil scan position error demodulators, in place of the video as in normal tracking. One of the demodulator electronic switches in each of the pupil demodulators is in the transmitting condition and one is in the nontransmitting condition. Thus the dc voltages are propagated through the demodulators with a polarity depending on which of the two demodulator switches is transmitting. These voltages cause a ramp output from the pupil integrators. When these ramps exceed a raster threshold voltage (± 7 volts in the pupil channels ± 10 volts in the corneal channels) the appropriate raster state sensor (all on card 6) switches its condition (e.g., it might be from A = "1" to A = "0", where A is the raster state logic signal for the pupil (x) raster). A change in condition of a raster state logic signal causes the associated demodulator switches to change transmission states (i.e., a switch that was transmitting becomes nontransmitting and vice-versa) and this in turn causes the dc voltage applied to the associated integrator to change polarity. This in turn causes the ramp direction (of that integrator output) to be reversed, and thus the system generates a sawtooth (triangular) waveform. The voltages applied to the x and y channels are chosen to make the half periods of these triangular waves approximately:

pupil x: 6 ms

pupil y: 60 ms.

These sawtooth waveforms are applied to the scan summing amplifiers producing a coarse 10 line raster scan of the image dissector aperture over the eye space. The video from the image dissector is applied to the pupil state sensor on card 8. When the video level exceeds a threshold level (determined by the setting of the pupil acquisition threshold control) the logic state of the acquisition comparator changes and the system is then held in the pupil track mode for 0.1 seconds (i.e., $Q = 1$). While in the pupil track mode the video is applied to the loss of pupil track comparator. When the video level falls below a threshold level (determined by the pupil loss threshold control) the pupil loss comparator changes its logic state and, if the system has been in pupil track for more than 0.1 sec, causes the system to go out of pupil track (i.e., $Q \rightarrow 0$).

When the system is in pupil track, the corneal time (time periods 32 - 64) may be devoted to either corneal search ($R = 0$) or to corneal track ($R = 1$). The corneal state is determined by card 7 (corneal state sensor) in which the video is applied to the corneal acquisition and corneal loss comparators, in a similar way to the operation of the pupil state sensor.

Eye direction is proportional to the output of the corneal integrators. These integrator outputs are applied, via electronic switches, to amplifiers on card 16 which have provision for front panel individual adjustment of gain and offset. The function of the electronic switches is to suppress the raster waveforms in the search mode. A 20 millisecond RC low pass filter is also incorporated into the output amplifier.

The signal (front panel) outputs provided in the Oculometer are

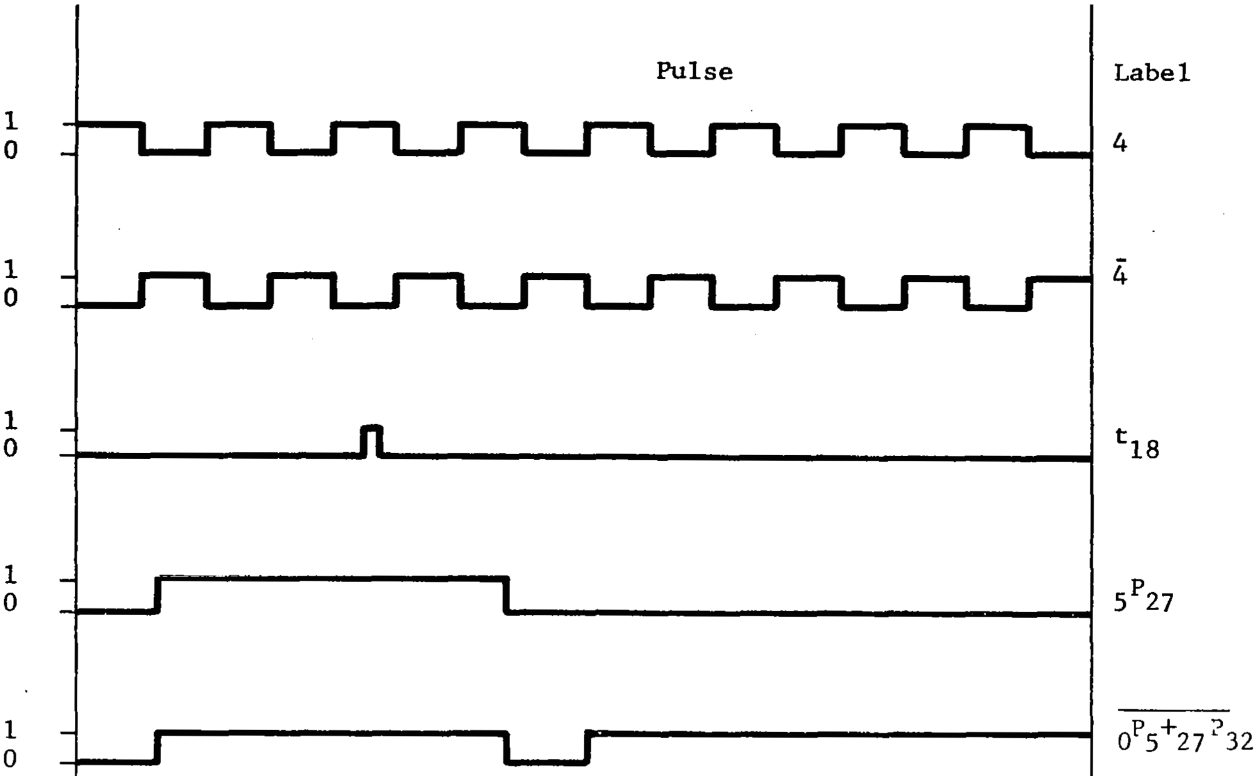
eye direction x $\Big\}$ card 16 amplifiers
eye direction y
pupil position x ($\int 2$)
pupil position y ($\int 3$)
pupil diameter ($\int 1$)
corneal logic signal (R)
pupil logic signal (Q)
video (A1)
timing pulses: start (t_o)
scan pulses: middle (t_{32})
scan pattern x (A 14)
scan pattern y (A 15)

In the pupil track mode (Q = 1), time periods 0-5 and 27-32 are not used for tracking During these periods the scanning aperture is brought to the central region of the pupil and made to execute a raster (line frequency 64 kHz, frame frequency 3.2 kHz) approximately .08 in. square (at the eye). This raster is termed the peak white sampling raster. The video level existing during time periods 0-5, 27-32 provides a measure of the peak white level. This is used in the half peak white clamp (on card 9) and in the peak white clamp (on card 7).

Detailed Circuit Description

Cards 1 and 2 In the previous discussion it has been seen that the tracking functions of the Oculometer are all based on sub-divisions of the basic Oculometer period of 2 ms (which is broken down into the 64 time periods). A master clock oscillator is used to generate all the timing, switching, and scan frequencies associated with the basic Oculometer period. The clock generator is a 256 kHz crystal oscillator. (Acutronics JC 15-22Z 256 kHz). Its 256 kHz sinusoidal output is applied to a chain of 9 flip flops. (all flip flops in the Oculometer are Fairchild 9926) thereby generating square wave signals 128, $\overline{128}$; 64, $\overline{64}$; 32, $\overline{32}$; 16, $\overline{16}$; 8, $\bar{8}$; 4, $\bar{4}$; 2, $\bar{2}$; 1, $\bar{1}$; 0.5, $\overline{0.5}$ (See Figure 22 for explanation of notation).

These signals are applied to a network of 6 input gates to generate the timing pulses t_0 t_2 t_3 t_5 t_7 t_{10} t_{14} t_{18} t_{22} t_{25} t_{27} t_{28} t_{32} t_{40} t_{48} t_{56} (See Figure 22). These pulses are used, later on, to synthesize the various timing pulses. Also generated on cards 1, 2 are the T pulses. This is zero at all times except for 2 microseconds starting 1 microsecond after the beginning of time period zero when it is logical 1. It is used to reset all flip flops in the Oculometer at the beginning of every 2 millisecond basic period.



$_5P_{27}/Q = {}_5P_{27}$ when $Q = 1$

$= 0$ when $Q = 0$

S_3 means drive for switch 3

switch 3 is transmitting when $S_3 = 1$

switch 3 is nontransmitting when $S_3 = 0$

$5\ P_{14}/Q,A = {}_5P_{14}$ when $Q = 1$

$= A$ when $Q = 0$

Figure 22 TIMING NOTATION

Card 3,4,5 Standard Oculometer signals are generated as specified in Table 3 (See Figure 22 for explanation of notation).

Card 6 This card contains all four raster threshold sensors. It generates the logic signals A,C, E and G (used to generate the raster scans).

Card 7 This card functions as the corneal state sensor. A simplified schematic is shown in Figure 23. The input video (from A1) is clamped to peak white. (That is, the capacitor shown in Figure 23 is charged up during time periods 0-5, 27-32, to the average peak white level. This charging action is accomplished when S32 becomes nontransmitting through the shorting of the signal line at S32 to ground. When this switch becomes transmitting, the short to ground is removed, and the capacitor is left (in a high impedance circuit) with a potential equal to the peak white level but of a polarity such as to cancel the peak white level dc component of the input video.)

Card 8 This card is the pupil state sensor and is very similar in operation to that of card 7 The video on which card 8 operates is unclamped, however, and is derived from card 0. A simplified schematic is shown in Figure 24.

Card 9 The functions performed on card 9 are:

(1) Clamping to one-half peak white (see Figure 25)

(2) Amplification of tracking video (output at A3 and A4)

(3) Injection of raster voltages

(4) Injection of dc voltage (via S33) to eliminate dc component of corneal video. This voltage is adjustable with a trim pot located at the top exposed edge of the card.

TABLE 3

SIGNALS GENERATED ON CARD 3

$_{o}P_{5} + {}_{27}P_{32}$ (= S_{33})

$_{7}P_{14} + {}_{18}P_{25}$

$_{27}\bar{P}_{5}$

$_{27}P_{5}$

$_{32}P_{64}$

$_{32}\bar{P}_{64}$

$_{5}P_{27}$

TABLE 4

SIGNALS GENERATED ON CARD 4

$$S_3 = {}_5P_{14}/Q,A$$

$$S_4 = {}_{18}P_{27}/Q,\bar{A}$$

$$(S_5)_1 = {}_5P_7 + {}_{25}P_{27}/Q$$

$$(S_5)_2 = C/\bar{Q}$$

$$(S_6)_2 = {}_{10}P_{22}/Q,\bar{C}$$

$$S_{27} = ({}_7P_{14} + {}_{18}P_{25})/Q$$

$$S_{32} = ({}_oP_5 + {}_{27}P_{32})/Q$$

$$S_2 = ({}_7P_{14} + {}_{18}P_{25})/Q$$

TABLE 5

SIGNALS GENERATED ON CARD 5

$S_{11} = S_{12} = {}_{32}P_{64}/Q$

$S_{14} = S_{16} = {}_{32}P_{64}/R$

$S_{23} = Scb = {}_{32}P_{64}/Q$

$S_{19} = S_{20} = {}_{32}P_{64}/(Q \text{ and } \bar{R})$

$S_{10} = {}_{40}P_{56}/R,\bar{G}$

$S_9 = {}_{32}P_{40}/R,G$

$S_7 = {}_{48}P_{64}/R\bar{E}$

$S_8 = {}_{32}P_{48}/R,E$

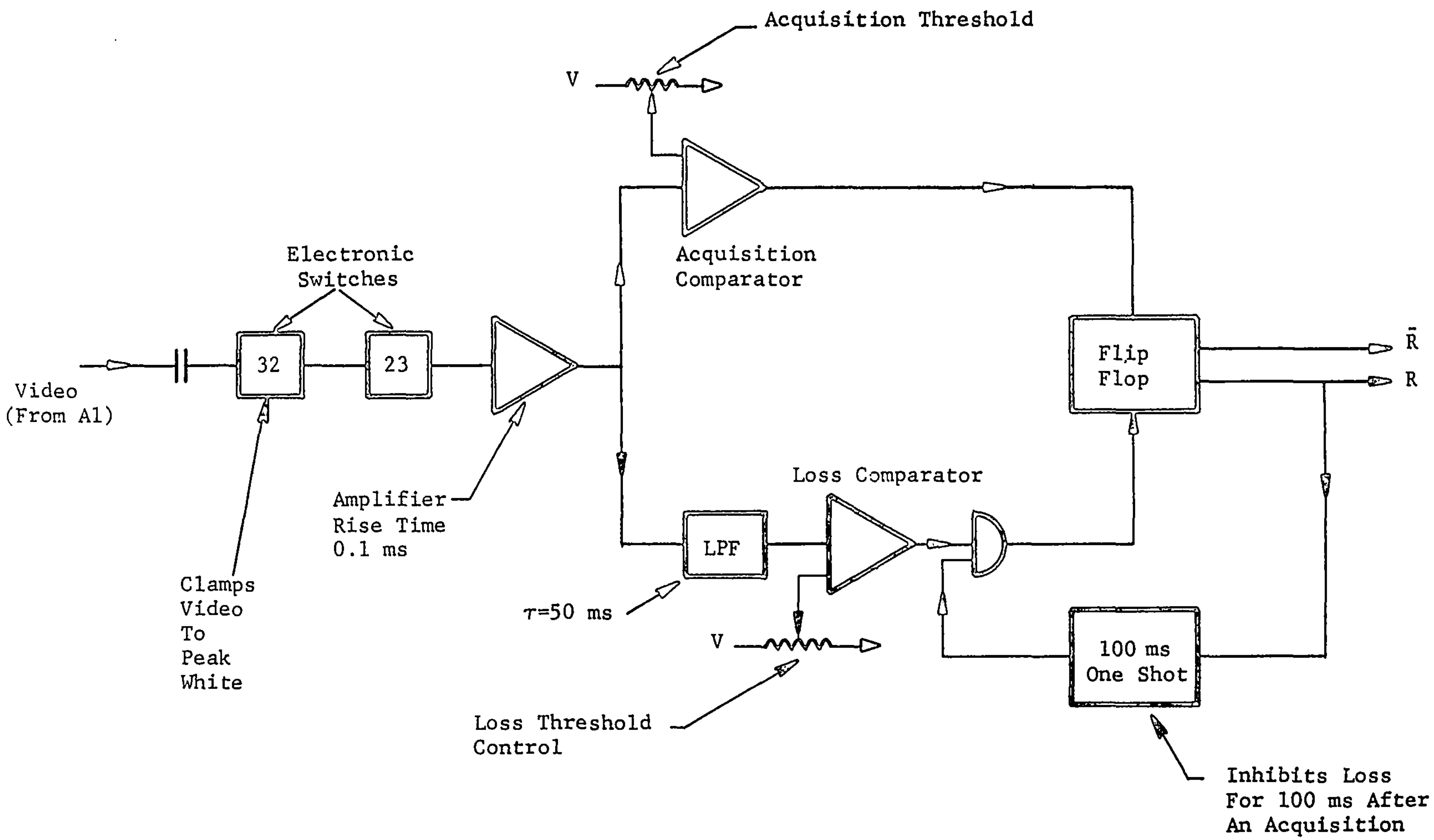


Figure 23 CORNEAL STATE SENSOR (Card 7) SIMPLIFIED SCHEMATIC

*When the Comparator Switches to The "Track" State it Latches on For 10 ms. There is a Negligible Latch Action on Switching to the "Loss" State

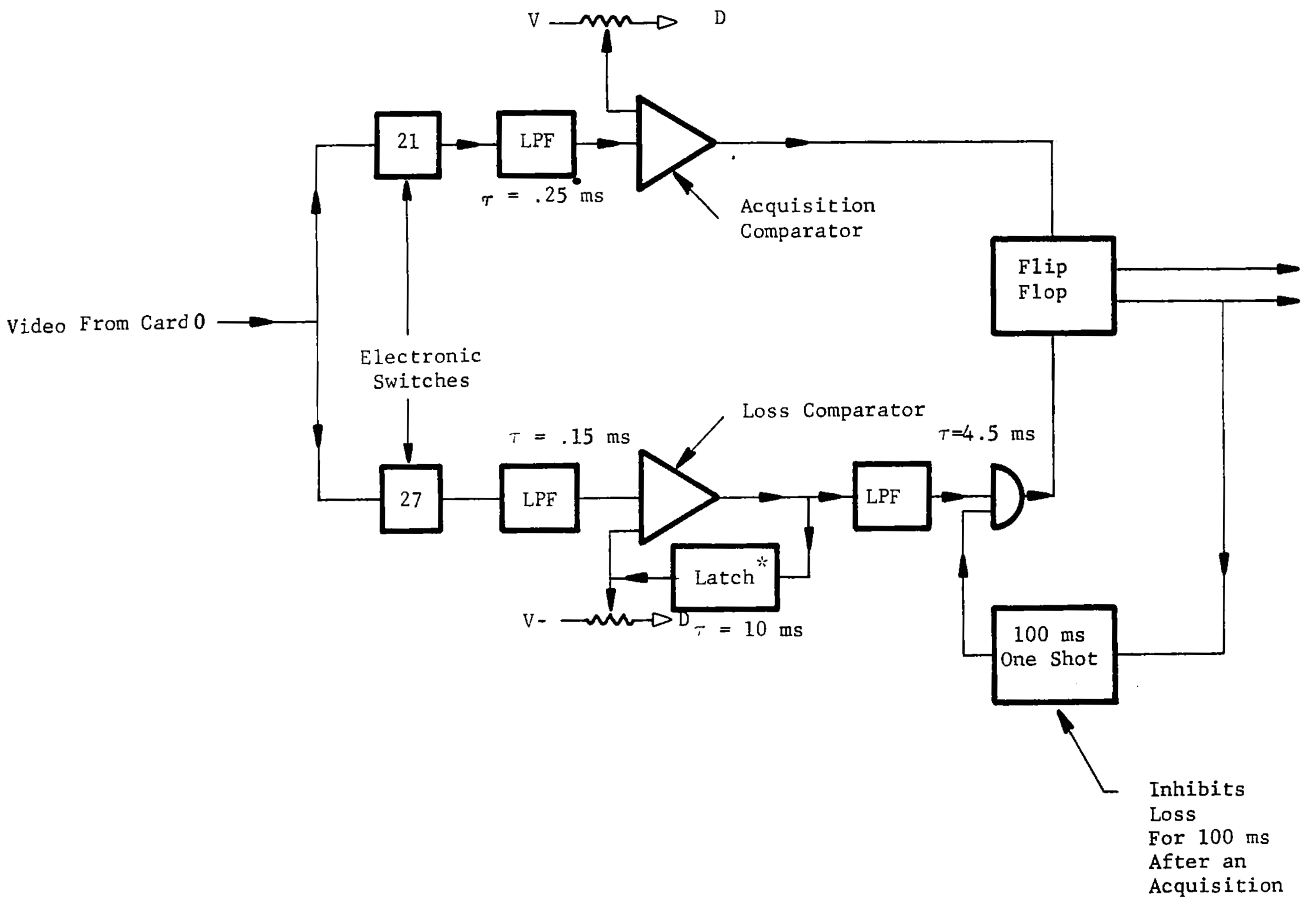
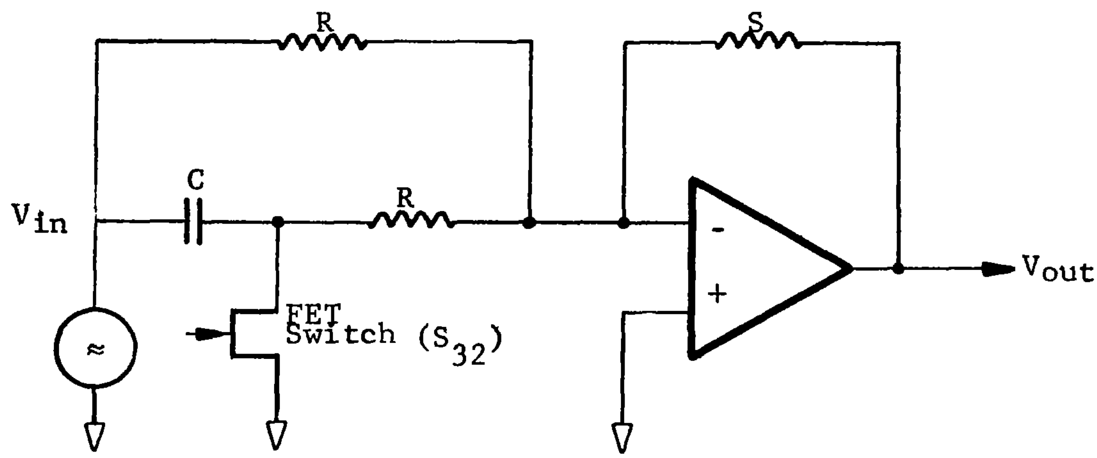


Figure 24 PUPIL STATE SENSOR (Card 8) SIMPLIFIED SCHEMATIC



Capacitor C charges up to peak white ($V_{in} = V_{pw}$) in time periods 0-5, and 27-32. The output from amplifier at other times is:

$$V_{out} = -\frac{V_{pw} S}{R} + \frac{V_{in} S\ 2}{R}$$

$$= \frac{2\ S}{R} \left(V_{in} - \frac{V_{pw}}{2} \right)$$

Since the average value of V_{in}, in pupil time, is nominally $\frac{V_{pw}}{2}$, the half peak white clamp assures that, nominally, V_{out} has zero average value in pupil time.

Figure 25 HALF PEAK WHITE CLAMP ON CARD 9

<u>Cards 10, 11, 12</u>   These cards contain the 5 Oculometer tracking loop circuits. Their operation has already been explained and the schematic circuits are shown in Figure 14.

<u>Card 13</u>   The circuits on this card modulate two input 1 kHz sinusoids (90° out of phase with each other). The modulation signal is a dc voltage from integrator 1 on card 10. Let V_{rms} be the rms voltage of the controlled 1 kHz and V_{dc} the control voltage.

The control action is specified by the equation

$$V_{rms} = 0.25 + 1.3\ V_{dc}$$

The zero to peak amplitude V_{peak} of the controlled 1 kHz is,

$$V_{peak} = 2\ V_{rms} = 0.5 + 2.6\ V_{dc}$$

The scale factor at the output of card 13 is 30 volts/inch. Let d be the pupil diameter in inches

$$V_{peak} = \frac{d}{2} \times 30 = 15\ d$$

$$V_{dc} = \frac{15\,d}{2.6} - \frac{0.5}{2.6}$$

$$= 5.8\ d - 0.2$$

This equation shows how the output voltage (V_{dc}) of integrator 1 is related to the pupil scan diameter in inches (d) referred to the eye.

Cards 14, 15 The scan signals are assembled on these cards under the action of electronic switches 11, 12, 13, 14, 15, 16, 28, 30 and 31, as shown in Figure 14. The two output attenuators are the trimpots mounted at the exposed edge of the cards. They have been set to give the correct scale factor at the eye and their setting should not normally be changed.

The deflection coils do not provide exactly orthogonal deflections. For this reason, a small fraction of the output of amplifier 15 is fed into amplifier 14 to correct for this lack of orthogonality.

The deflection characteristics of the Oculometer were measured by tracking an artificial pupil, on a movable x y carriage mounted at the eye space. In Figure 26 the position coordinates (relative to arbitrary orthogonal axes which are parallel to the normal x and y axes at the eye space) of the artificial pupil are plotted for the five cases defined by: integrator 2 output, 0 ± 1 volt, integrator 3 output: 0 ± 1 volt.

Card 16 This card contains the eye direction output amplifiers and regulated power supplies for +12 volts, +15 volts, -15 volts and -6.2 volts. Trimpot adjustments for these voltages are located at the exposed edge of the card.

Card 0 Card 0 has two functions:

1. the input video from A1 is inverted and amplified by 2.5 times and applied to card 8.
2. generation of $S_{22} = {}_{32}P_{64}/Q$ when $R = 0$

   $= Q$ when $R = 1$

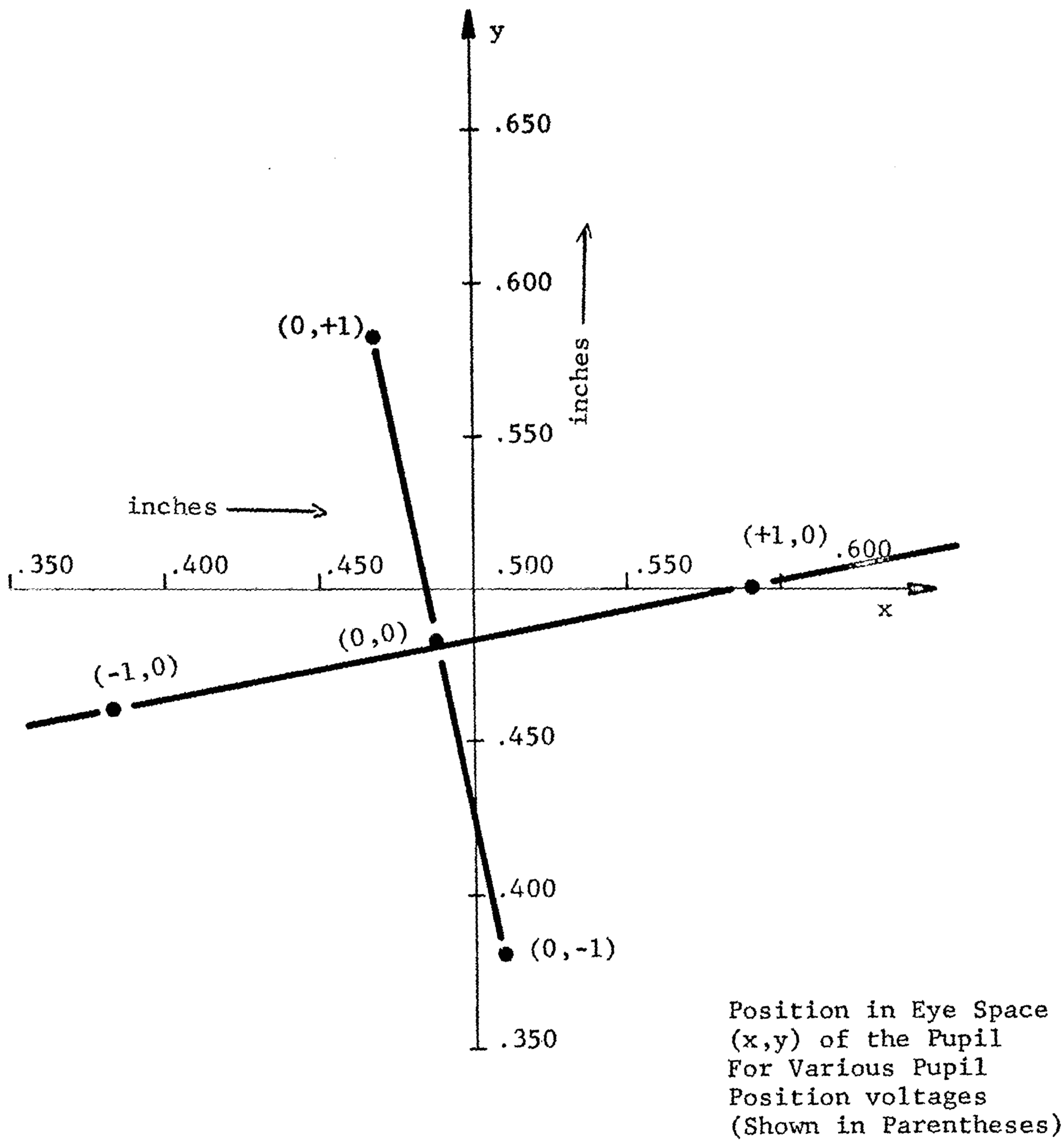


Figure 26 IMAGE DISSECTOR AXES

Power Supplies

The power supplies used by the Oculometer are

1 Technipower MC 3.7 - 4.0 (+3.6 logic supply)
2 Technipower MC 19.2 - 4.0 (± 20 V for deflection amplifier)
1 Technipower SCR 10.0 - 12.0 (8.5 V for filament lamp)
1 Del Electronics 2.5 RN 4-1 (2.0 kV image dissector supply)

These power supplies are located with the deflection amplifier on the faceplate of electronics rack.

PERFORMANCE

As a preliminary evaluation of performance, the Oculometer eye direction outputs (x and y) were recorded on a strip chart as the eye fixated steadily at each of a horizontal row of points each 1 in. apart at a range of 53 in. (These points thus appear to be approximately 1° apart at the eye). These recordings are shown in Figure 27. It can be seen that the combined noise level of the eye and of the Oculometer is about 0.5°. The dynamic range of the device is about ±15 degrees in both axes: it is limited by

(a) the requirement that the corneal reflection stay within the pupil
(b) upper eye lid obscuration when looking more than ten degrees below the Oculometer axes.

A simple demonstration experiment with the Oculometer is shown in Figure 28.

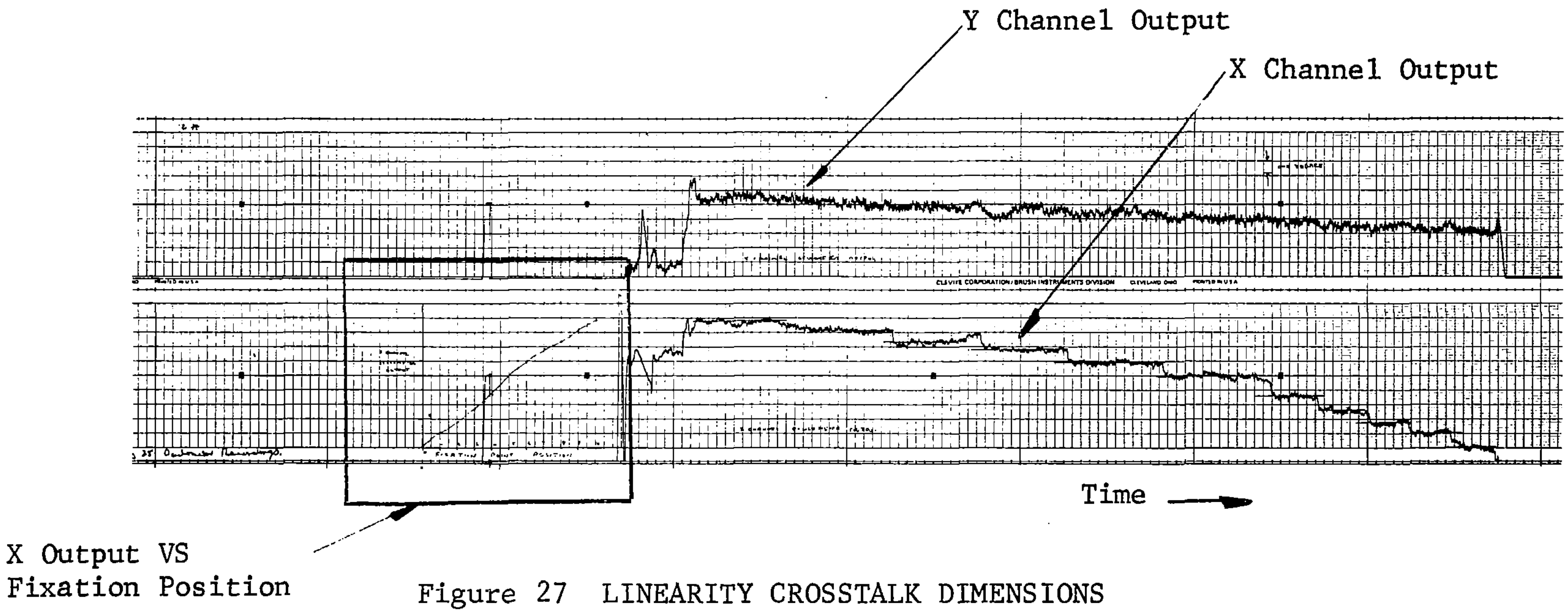
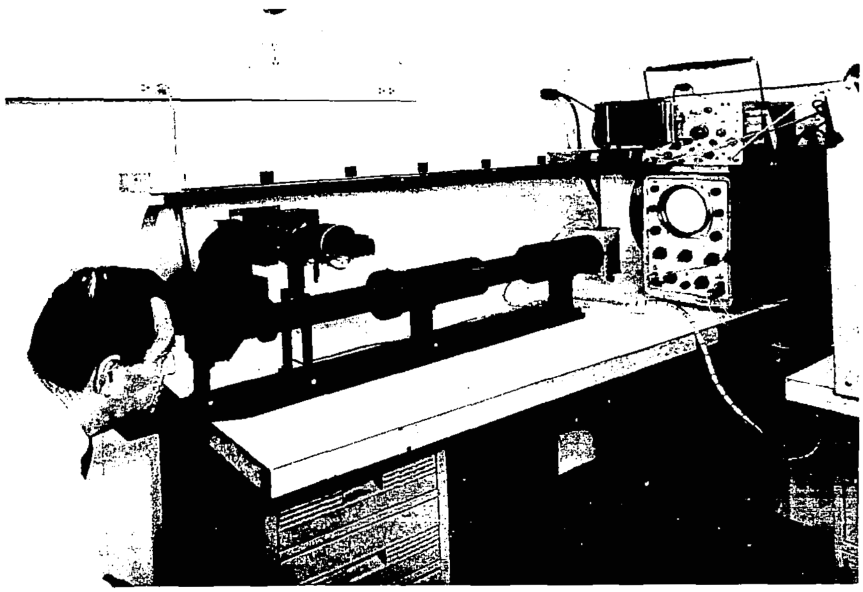
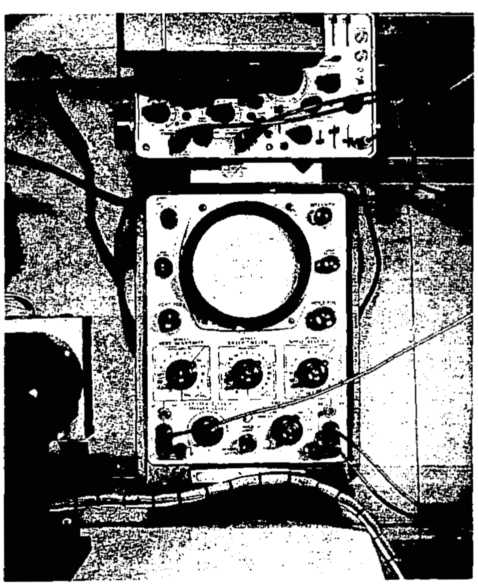


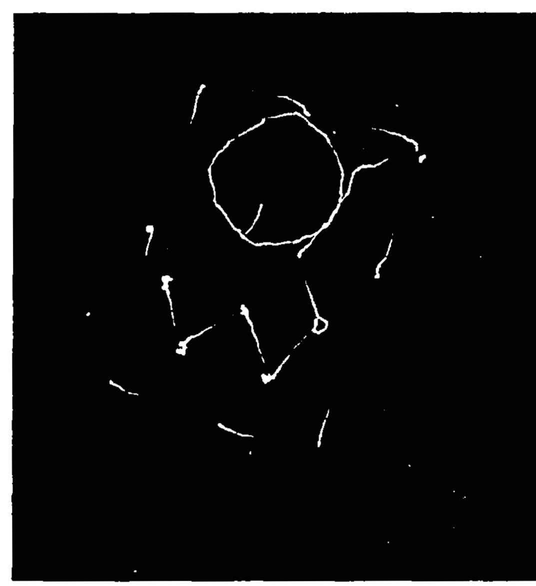
Figure 27 LINEARITY CROSSTALK DIMENSIONS



A



B



C

The operator (A) scans his eye over the outer edge of the Oscilloscope (B), the circular edge of the CRT Screen, and then fixates at each of the six control knobs. The Oculometer measures the direction of his eye during this operation and a record of the Oculometer output (C) shows an "eye-drawing" of the Scope.

Figure 28 EYE TRACKING WITH THE OCULOMETER

APPENDIX A

EYE REFLECTIVITY MEASUREMENTS AND ANALYSIS

The following analysis is based on a first order approximation of the eyeball optics.

Referring to Figure A.1 with the following notation:

k_R = retinal reflectance

τ = transmission of eye media

d = pupil diameter

a = distance from eye lens to retina

B_s = light source brightness

L = camera lens to film plane distance

A_m = area of camera lens aperture

t_c = collection optical system transmission

t_I = illumination optical system transmission

S = pupil to camera lens distance

A_s = source area

ρ = reflection factor of cornea

The total quantity of illumination (Q'_p) incident at the eye pupil is given by

$$Q'_p = A_s B_s \frac{\pi d^2}{4 S^2} t_I \text{ watts} \tag{A-1}$$

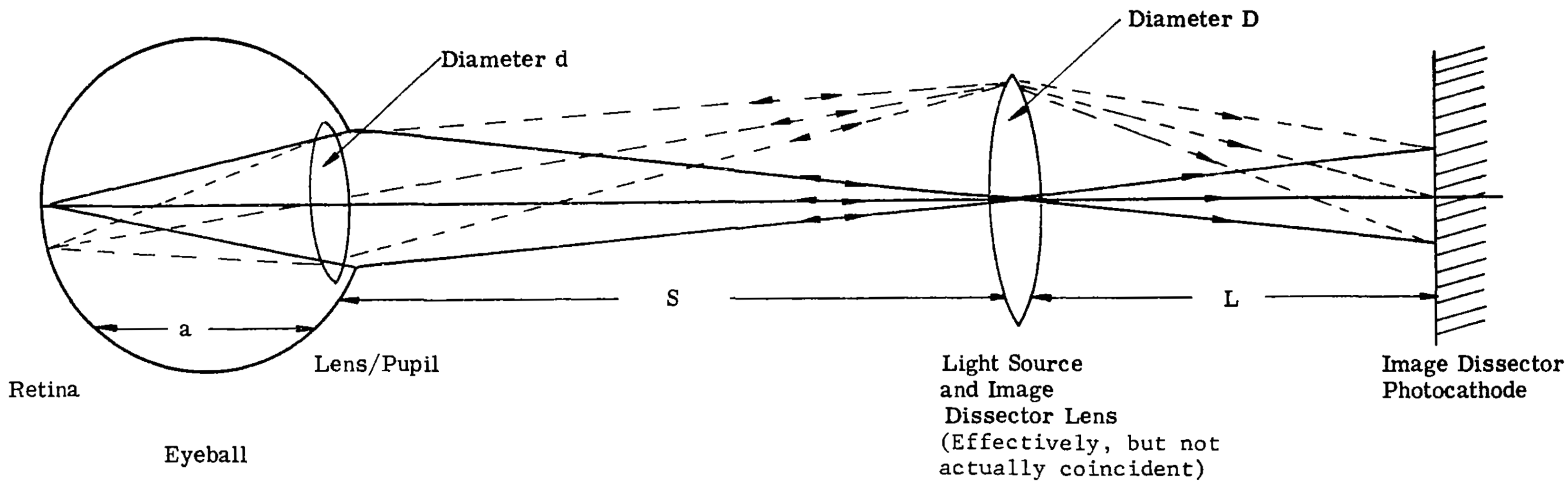


Figure A.1 UNFOLDED VIEW OF NEW PUPIL IRIS BOUNDARY ILLUMINATION TECHNIQUE

The area of the Retinal image is $(\frac{a}{s})^2$ A_s and the retinal illumination is

$$E_R = \frac{Q'_p \tau}{A_s} (\frac{S}{a})^2 \text{ watts/cm}^2 \qquad \text{(A-2)}$$

Retinal brightness is

$$B_R = k_R \frac{E_R}{\pi} \text{ watts/steradian/cm}^2 \qquad \text{(A-3)}$$

The bright image on the retina radiates light back to the pupil. The total amount collected is Q''_p where

$$Q''_p = \tau (\frac{a}{S})^2 A_s B_R \frac{\pi d^2}{4 a^2} \qquad \text{(A-4)}$$

The area of the pupil image on the photocathode is

$$\frac{\pi d^2}{4} \quad \frac{L^2}{S^2}$$

Thus the illumination of the photocathode is given by E_{pc}

$$E_{pc} = Q''_p t_c \frac{4 S^2}{\pi d^2 L^2} \lambda \qquad \text{(A-5)}$$

Where λ is the fraction of the area of the source that is contained within the area of the collection lens (i.e., $0 \leq \lambda \leq 1$).

Let f be the focal length and F the f/number of the lens. Let m be the linear magnification between pupil and pupil image on the photocathode.

Then

$$\frac{4 A_m}{\pi} = (f/F)^2$$

$$1/S + 1/L = 1/f$$

$$m = L/S$$

i.e., $\frac{1}{L}(1 + m) = 1/f$

$$\therefore \quad \frac{4\ A_m}{\pi} = \left[\frac{L}{(1 + m)\ F}\right]^2 = \left[\frac{L}{m\ F'}\right]^2 \qquad \text{(A-6)}$$

Where F' is the f/number of the rays diverging from the eye.

From equations 1, 2, 3, 4 and 5

$$E_{pc} = \frac{(t_c\ 4\ S^2)\ (\tau\ a^2\ A_s\ \pi\ d^2)\ (k_R)\ (\tau\ S^2)\ (A_s\ B_s\ \pi\ d^2\ t_I)}{(\pi\ d^2 L^2)\ (S^2\ 4\ a^2)\ (\pi)\ (A_s\ a^2)\ (4\ S^2)}$$

$$= \frac{t_c\ t_I A_s k_R\ \tau^2\ B_s\ d^2 \lambda}{L^2\ a^2\ 4}$$

Substituting for L from equation 6

$$E_{pc} = \lambda\ \left(\frac{A_s}{A_m}\right)\ (k_R\ \tau^2)\ \left(\frac{d}{a}\right)^2\ \left(\frac{1}{m^2}\right)\ \left(\frac{1}{F'}\right)^2\ \left(\frac{\pi\ B_s}{16}\right)\ t_I t_c \qquad \text{(A-7)}$$

Consider now a diffuse reflector located in the plane of the eye. The illumination at the reflector is E_{RR}, given by

$$E_{RR} = \frac{A_s\ B_s\ t_I}{S^2}$$

Let k_D be the reflectance factor of the diffuse reflector.

The brightness of the reflector is

$$B_{RR} = k_D \frac{E_{RR}}{\pi}$$

The illumination of the screen is E_{pcr} where

$$E_{pcr} = \frac{\pi\, B_{RR}\, t_c}{4F'^2\, m^2}$$

$$= \frac{\pi\, k_D\, A_s\, B_s\, t_I\, t_c}{4F'^2\, m^2\, \pi\, S^2}$$

$$= \frac{k_D\, A_s\, B_s\, t_I\, t_c}{4F'^2\, m^2\, S^2}$$

The ratio, R, of the Illuminations E_{pc} and E_{pcr} is

$$R = \frac{E_{pc}}{E_{pcr}} = \lambda \left(\frac{A_s}{A_m}\right) (k_R\, \tau^2) \left(\frac{d}{a}\right)^2 \frac{\pi}{4} \frac{S^2}{k_D\, A_s} \qquad \text{(A-8)}$$

Substituting from equation (6) for A_m

$$R = \lambda \left(\frac{k_R\, \tau^2}{k_D}\right) \left(\frac{d}{a}\right)^2 F'^2 \qquad \text{(A-9)}$$

The brightness of the corneal reflection is $B_s\, t_I\, \rho$ watts/cm^2/steradian. The illumination E_{cr} of the image of the corneal reflection at the photocathode is given by

$$E_{cr} = \frac{\pi \left[B_s\, t_I\, \rho\right] t_c}{4\, F'^2\, m^2}$$

The ratio of the intensity of the corneal reflection image to that of the pupil image is

$$\frac{E_{cr}}{E_{pc}} = \frac{4\ \rho}{\lambda \left(\frac{A_s}{A_m}\right) k_R\ \tau^2\ \left(\frac{d}{a}\right)^2} \qquad \text{(A-9)}$$

Photographic Tests

In order to confirm, in practice, the new illumination technique, and to measure the effective reflectance factor ($\tau^2\ k_R$) of the eye in this mode, a series of photographs were taken.

A sketch of the optical system used in testing is shown in Figure A-2. The eye is illuminated by the magnified image of a tungsten filament lamp. The pupil of the eye is imaged on the film plane of a Honeywell Pentax camera. The filament image placement was such that its center appeared (to the subject's eye) physically coincident with the center of the camera lens aperture.

In this configuration, simple theory predicts that all light emerging from the pupil will reach the film plane provided that the following two conditions hold:

(a) the effective camera lens aperture is larger than or equal to the filament image area;

(b) the subject's eye is focused on a point in the plane of the lens aperture.

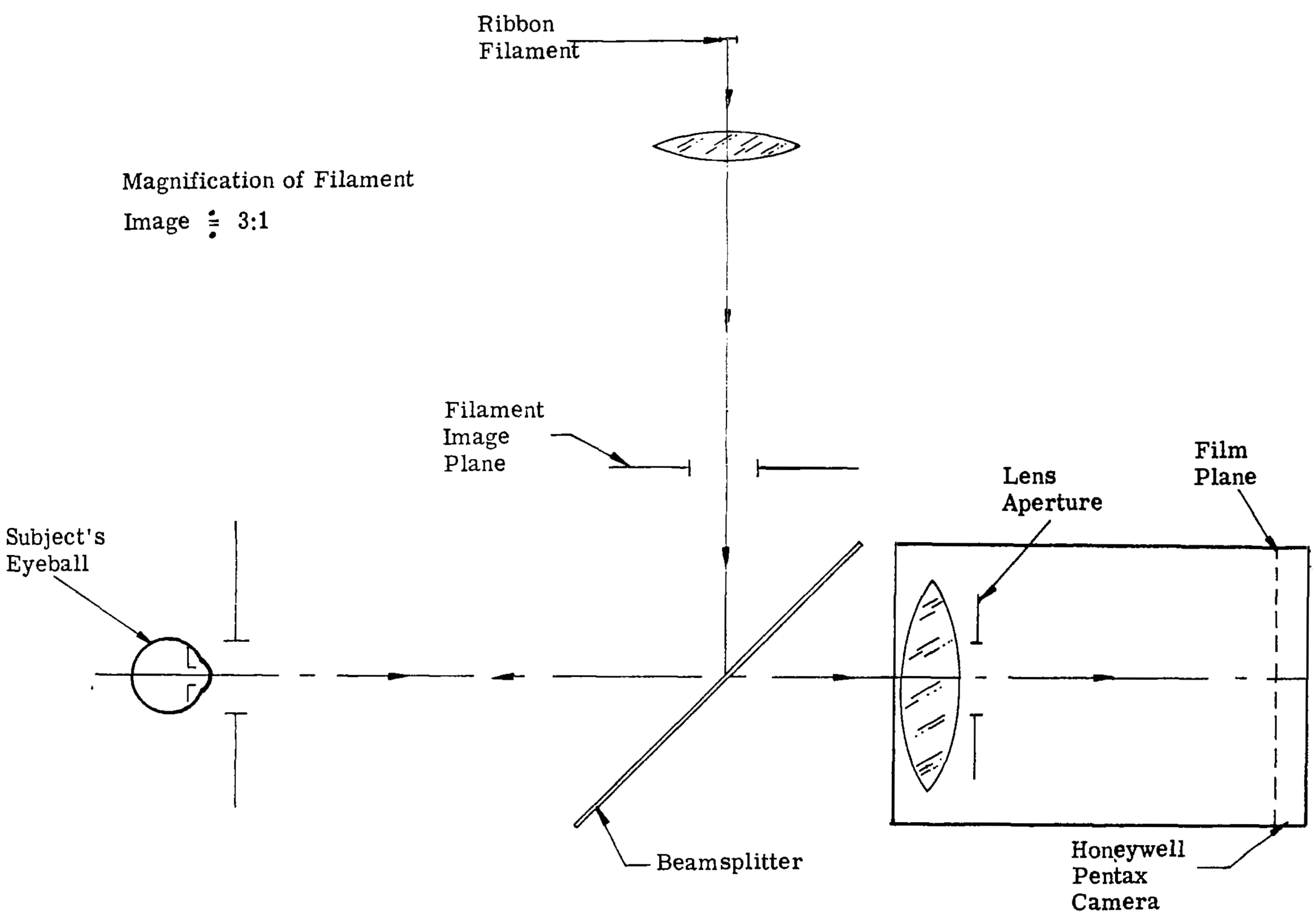


Figure A.2 OPTICAL SCHEMATIC OF EXPERIMENT

The flux density in the pupil image (on the film) will then be given by equation (7) above.

In the experiments, pupils of a number of subjects were photographed in three spectral bands. For comparison purposes, a diffuse reflector (Fiberfrax 970 JH ceramic paper) was also periodically photographed. Densitometry of the resulting negatives then allowed experimental determination of the ratio, R. The diameter of the pupil of each subject was always measured and recorded. The distance "a" was assumed to be 20 mm for each subject. Then all the variables in equation (9) except for $\tau^2 k_R$ were known, and the values of $\tau^2 k_R$ could be calculated.

As was mentioned, the pupil was photographed in three spectral bands. The relative spectral sensitivities of these bands are shown in Figure A-3.

Other relevant variables in these tests are shown in Table A-1.

Experimental Results and Their Interpretation

The results of these tests are shown in Table A-2. As can be seen, the measured value of $\tau^2 k_R$ is approximately 0.02 in each of the three wavelength bands.

The following statements should be borne in mind in the interpretation of these results. The value of $\tau^2 k_R$ was calculated on the basis of the simple theory above. The assumption was made that the eye was focused on the plane of the lens aperture (or the plane of the filament image). In actuality, it was difficult for

TABLE A.1

EXPERIMENT CONDITIONS

Variable	0.6 - 0.7μ Test	0.7 - 0.8 μ Test	0.8 - 0.9 μ Test
Source Area	0.75 sq cm	0.75 sq cm	1.2 sq cm
Lens Aperture Area	0.95 sq cm	0.95 sq cm	0.95 sq cm
Filters Used	Wratten #25	Wratten #25	Wratten #25
	B&L #90-7	Wratten #34A	Wratten #34A
	Ealing #26-305	Ealing #26-305	
Film	High Speed IR	High Speed IR	High Speed IR
Filament Temp.	3000°K	3000°K	2300°K
Approximate Collection f/number	47.5	57.5	47.5

Note: These curves are normalized such that the areas under each curve are equal.

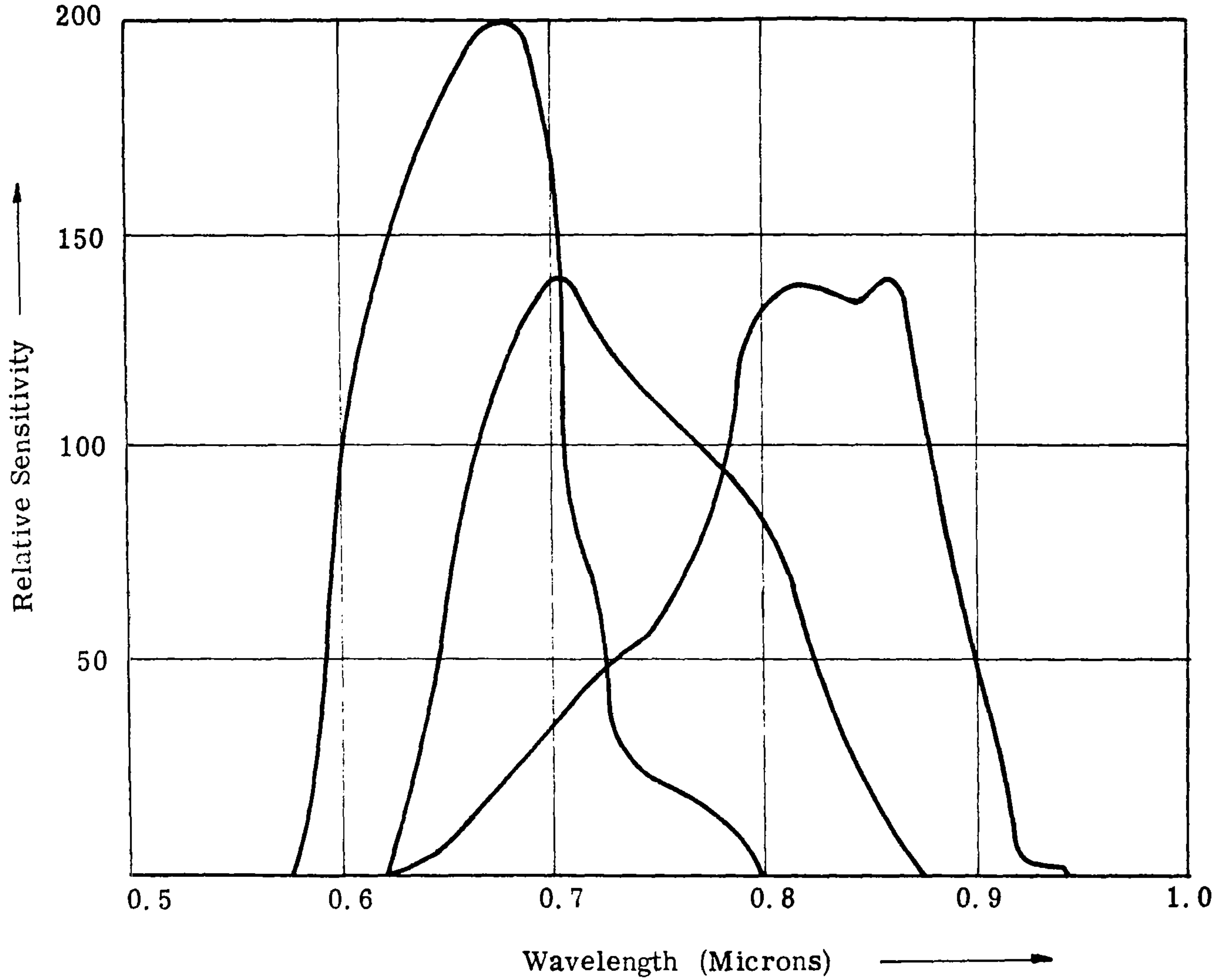


Figure A.3 RELATIVE SPECTRAL SENSITIVITIES OF THREE PHOTOGRAPHIC TESTS

Table A.2

SUMMARY OF TEST RESULTS
FOR "BRIGHT PUPIL" PHOTOGRAPHIC TESTS
(Gives value of τ^2 k_R for three bands)

Subject	τ^2 k_R 0.6 - 0.7 μ	τ^2 k_R 0.7 - 0.8μ	τ^2 k_R 0.8 - 0.9 μ
Mason	.0277	.0308	.0270
Zudek	------	-----	.0304
Jennette	.0267	.0237	.0235
Moscaritolo	-----	.0201	.0161
Nagigian	.0178	.0180	.0165
Merchant	.0294	-----	.0214
Plummer	-----	.0236	.0178
Callahan	-----	.0238	.0220
Stetson	-----	.0184	.0208
McCarthy	.0261	.0288	.0263
Holt	-----	.0184	.0143
Levandowski	-----	.0187	.0195
Popp	-----	.0182	.0178
Piacentini	-----	.0182	.0182
Kelly	-----	.0233	.0191
Gallagher	-----	.0323	.0307

the subject to focus on that plane (largely for psychological reasons). If the eye was really focused at infinity, then simple theory shows that not all light emerging from the pupil will pass through the camera lens aperture as assumed. In several instances, the camera lens aperture was opened up so as to be much larger then the filament images; in these instances, the pupil luminance appeared to increase, which is consistent with the eye being focused on some plane other than that of the light source.

It is suspected, therefore, that the real values of $\tau^2 k_R$ may be somewhat greater (perhaps by a factor of two) than the measured values shown in Table A-2. What Table A-2 does present are effective values of $\tau^2 k_R$ for the given experimental conditions, which closely duplicate the conditions that will exist in the actual Oculometer.

APPENDIX B

Calculation of Oculometer Signal/Noise Ratio

The general expression for the pupil signal, S, in units of electrons per sample time, is given as follows:

$$S = E_{pc} (K) \tau_s A_{ap} \overline{Q} \tag{B-1}$$

where

E_{pc} = flux density at photocathode due to the pupil (watts/cm^2)

K = a constant which is equal to approximately 4.6×10^{18} photons per watt-sec, for a wavelength of 0.9 micron

τ_s = sample time

A_{ap} = area of ID tube aperture

$\overline{Q}$ = mean photocathode quantum efficiency

The value of $\overline{Q}$ is determined by the following formula:

$$\overline{Q} = \frac{\int_{\lambda_1}^{\lambda_2} \frac{dE_{pc}(\lambda)}{d\lambda} \quad Q\ (\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} dE_{pc}\ (\lambda)} \tag{B-2}$$

where λ_1 and λ_2 are limits of oculometer wavelength band.

From equation (A-7) (with $A_s = A_m$ and $\lambda = 1$), the expression for E_{pc} is given as follows:

$$E_{pc} = \left(k_R\ \tau^2\right) \left(\frac{d}{a}\right)^2 \left(\frac{1}{m^2}\right) \left(\frac{1}{F'^2}\right) \left(\frac{\pi\ B_s}{16}\right) \quad t_I\ t_C$$

where

k_R = effective reflectance of retina

τ = transmission of ocular media

d = diameter of pupil = 3 mm minimum

a = focal length of eye $\doteq$ 20 mm

m = magnification of eye image $\doteq$ 1

F' = f/number of optics $\doteq$ 50

t_C = transmission of collection optics

B_s = brightness of source

t_I = transmission of illumination optics

The maximum usable value of the quantity $t_I\ B_s$ is determined by the maximum safe level of radiation that can fall on the human retina for long periods of time.

From information obtained from the Retina Foundation (O. Pomerantzeff), the maximum radiation level at the retina which will not cause damage is 0.75 calories/cm/sec, i.e., 3 watts/cm^2. A 20 times safety factor will be utilized and the maximum value of retinal illumination will be limited to 0.15 watts/cm^2.

The retina flux density is given by the following expression:

$$I_R = \left[\frac{d}{a}\right]^2 (B_s\ t_I) \left[\frac{\pi}{4}\right] \tau$$

The maximum usable value of $B_s\ t_I$ can then be calculated by letting d equal 7 mm and "a" equal 20 mm. To be conservative, it will be assumed (here) that $\tau = 1$.

Then,

$$(B_s\ t_I)_{max} = 1.5 \text{ watts/cm}^2\text{/steradian} \tag{10}$$

The value of $\tau^2 k_R$ has been experimentally determined to approximately 0.02 (see Table A-2). The value of t_C is approximately 0.4. The value of E_{pc} may now be calculated.

$$E_{pc} = (0.02) \left(\frac{3}{20}\right)^2 \frac{1}{(50)^2} \left(\frac{\pi}{16}\right) (1.5)\ (0.4)$$

$$E_{pc} = 2.12 \cdot 10^{-8} \text{ watts/cm}^2$$

It should be noted that this value of E_{pc} holds for a pupil diameter of 3mm which is equal to about the minimum to be expected in most situations. The pupil signal can now be calculated from equation (B.1). The basic sample time τ_s is one millisecond and the diameter of the ID tube aperture is 20 mils at the eye.

The value of $\bar{Q}$ is dependent both on the type of photocathode used, and on the wavelength band of the Oculometer radiation. Several relevant cases are presented below.

For an S-20 surface and radiation between 0.7 and 0.8 micron, $\bar{Q}$ equals 0.012.

For an S-20 surface and radiation between 0.75 and 0.85 micron, $\bar{Q}$ equals 0.0035.

For an S-1 surface and radiation between 0.7 and 0.8 micron, $\bar{Q}$ equals 0.0039.

For an S-1 surface and radiation between 0.75 and 0.85 micron, $\bar{Q}$ equals 0.0039.

For an S-1 surface and radiation between 0.8 and 0.9 micron, $\bar{Q}$ equals 0.0035.

Table B.1 gives the values of signal and signal-to-noise ratio for the various values of $\bar{Q}$. It is assumed that shot noise in signal is the only noise source.

Table B.1

OCULOMETER SIGNAL DUE TO PUPIL SCAN

Photocathode	Wavelength Band	(Photoelectrons per sample time)	(Signal-To Noise Ratio)
S-20	0.7 - 0.8 μ	2048	45
S-20	0.75 - 0.85 μ	602	24
S-1	0.7 - 0.8 μ	672	26
S-1	0.75 - 0.85 μ	672	26
S-1	0.8 - 0.9 μ	601	24

The worst case dark current with an S-1 surface (at 20°C) is 10^{-11} amp/cm at the photocathode. With a 20 mil aperture the total dark current will be

$$I_{DK} = 10^{-11} \times 2.032 \times 10^{-3} = 2.032 \times 10^{-14} \text{ amp}$$

Over a 1.0 ms sample time the number of thermal electrons emitted will be

$$N_e = 10^{-3} \times 2.032 \times 10^{-14} \times 6 \times 10^{18} = 122$$

From Table B.1 the corresponding number of signal electrons is about 602, so that, even in a worst case of dark current, the noise in the dark current will be negligible compared to the shot noise in signal.

It has been shown in Appendix A that the ratio of the brightness of the pupil and corneal reflection images is

$$\frac{E_{cr}}{E_{pc}} = \frac{4\rho}{\lambda \left[\frac{A_s}{A_m}\right] k_R \, \tau^2 \left[\frac{d^2}{a^2}\right]}$$

$\rho \approx 2.5 \times 10^{-2}$ ($\left[\frac{n-1}{n+1}\right]^2$ where n = 1.376)

$\lambda \; A_s/A_m = 1$

$k_R \tau^2 \approx 2 \cdot 10^{-2}$

$(d/a)^2 \approx 1/50$ (for a 3mm pupil)

$$\therefore \frac{E_{cr}}{E_{pc}} \approx \frac{10 \times 10^{-2} \times 50}{2 \times 10^{-2}} = 250$$

The diameter by the corneal reflection (at the eye) is about 0.0027 in. Thus the ratio of the image dissector signals, for the two images, is

$$\frac{S_{cr}}{S_{pc}} \approx 250 \times \left[\frac{2.7}{20}\right]^2 = 4.6$$

The Oculometer signal for the corneal reflection can thus be estimated from the pupil signal given in table B.1 by multiplying by 4.6

Selection of Wavelength Band

The previous analysis has shown that an adequate signal-to-noise ratio can be obtained at any of the three bands investigated (0.6 μ, 0.8 μ - 0.9 μ). (The possible use of near ultraviolet radiation was rejected because of the low transmission factor of the ocular media at the blue end of the spectrum. The new pupil illumination method depends upon transmission of radiation through the ocular media between the retina and the front of the eye.)

The final choice of the operating band was made to satisfy the requirement for the use of invisible radiation. The apparent brightness of the light source is $B_S t_i$. From equation (10) this is 1.5 watts/cm^2/steradian. The apparent visibility of this source is

$$V = 600 \times 10^3 \times 1.5 \times V_\lambda \text{ candles/sq ft}$$
$$\approx V_\lambda \times 10^6 \text{ candles/sq ft}$$

where V_λ is the relative visual response at the wavelength (λ) (i.e., $V_\lambda = 1$ at $\lambda = 0.505\ \mu$).

At 0.85 μ

$$V_\lambda = 1.2 \times 10^{-7}$$

$$\therefore V = 0.12 \text{ candles/sq ft}$$

APPENDIX C

DEMODULATION SCALE FACTORS AND TRACKING NOISE

Let V_{pw} be the pupil signal level corresponding to peak white (that is when the image dissector scanning aperture is wholly within the pupil). Let the pupil scan be displaced by an amount (x'', y'') (referred to the eye) from the true position of the pupil. Then, to first order, the two 1 kHz modulation components of the pupil video will be:

$$V_{pw} \frac{x(0.02)\ 4}{\pi\ (0.02)^2}\ ,\quad V_{pw} \frac{y(0.02)4}{\pi(0.02)^2}$$

$$= \frac{200}{\pi} x\ V_{pw} \quad ,\quad \frac{200}{\pi} y\ V_{pw}$$

The corresponding error signals generated by the demodulation functions shown in Figure 18 will be:

$$\ell_x = \frac{200}{\pi} x\ V_{pw} \frac{1}{64} \left\{ \int_5^{14} \sin \frac{2\pi n}{32}\ dn - \int_{18}^{24} \sin \frac{2\pi n}{32}\ dn \right\}$$

where n is the time period.

Converting to degrees (1 time period = 11.25°)

$$\ell_x = \frac{200}{4\pi^2} x\, V_{pw} \left[(\cos 56.25° - \cos 157.5°) - (\cos 202.5° - \cos 303.75°) \right]$$

$$= \frac{200}{4\pi^2} x\ V_{pw} \left[\cos 56_{NB}25 + \cos 22.5° + \cos 22.5° + \cos 56.25° \right]$$

$$= \frac{200}{2\pi^2} x\ V_{pw} \left[.554 + .924 \right]$$

$$= \frac{200\ x\ V_{pw}}{2\pi^2}\ 1.478$$

$$\approx 15\ x\ V_{pw}$$

Similarly for y:

$$\ell_y = \frac{200}{\pi} y \frac{V_{pw}}{64} \left\{ 3 \int_5^7 \cos \frac{2\pi n}{32} \, dn - \int_{10}^{22} \cos \frac{2\pi n}{32} \, dn \right.$$

$$\left. + 3 \int_{25}^{27} \cos \frac{2\pi n}{32} \, dn \right\}$$

$$= \frac{200}{4\pi^2} y V_{pw} \left\{ 3 \, [\sin 78.75° - \sin 56.25°] \right.$$

$$\left. - [\sin 247.5° - \sin 112.5°] + 3[\sin 303.75° - \sin 281.25°] \right\}$$

$$= \frac{200}{4\pi^2} y V_{pw} \left\{ 3[\sin 78.75° - \sin 56.25°] \right.$$

$$\left. + [\sin 67.5° + \sin 67.5°] - 3[\sin 56.25° - \sin 78.75°] \right\}$$

$$= \frac{200 y}{2\pi^2} V_{pw} \left[3(\sin 78.75° - \sin 56.25°) + \sin 67.5° \right]$$

$$= \frac{200}{2\pi^2} y V_{pw} [1.37] \approx 14 \, y \, V_{pw}$$

For the pupil channel, the error signal, ℓ_p is given by

$$\ell_p = \frac{200}{\pi} d \frac{V_{pw}}{64} \{14\} = 14 \, V_{pw} d$$

where d is the pupil radius error in inches.

For the case of the corneal channel, the peak corneal signal (when the corneal reflection is totally within the aperture) is shown, in Appendix B, to be 4.6 V_{pw}. Although the nominal reflection diameter is 0.0027 in., a 0.5 in. axial position error of the eye can be assumed which will cause the reflection to be defocussed to 0.01 in. diameter. The scan error signals, for the corneal case (E_x, E_y) may be calculated in the same manner as for the pupil channel;

$$E_x = \frac{400}{4\pi^2} \times (4.6 \; V_{pw}) \left[(\cos 0 - \cos 180) - (\cos 180 - \cos 360)\right]$$

$$(E_x = E_y)$$

(the factor 400 appears here in place of the 200 in the corresponding pupil expression because the resolution-determining reflection diameter is 0.01 in., i.e., one half of the aperture diameter 0.02 in. which determines resolution in the case of the pupil)

$$\therefore \; E_x \simeq 40 \times 4.6 \; V_{pw} = 184 \times V_{pw}$$

It is shown in Appendix B that the peak white signal level (V_{pw}) is due to a flux of 600 photoelectrons per millisecond.

The total number of photoelectrons, per one millisecond sample time, involved in the pupil x demodulation process is 300 x $\left(\frac{18}{32}\right)$ and for pupil y demodulation 300 x $\left(\frac{24}{32}\right)$.

The tracking noise (X_n, y_n) will be due to statistical fluctuations in the above, i.e.

$$|15| \times (x_n) \; |600| = \sqrt{\frac{(300) \times (18)}{32}}$$

$$14 \times |y_n| \times (600) = \sqrt{\frac{(300)(24)}{32}}$$

$$\therefore x_n = \frac{1}{15} \sqrt{\frac{9}{(600) \times (32)}} \approx (1.4) \quad 10^{-3} \text{ inches}$$

$$\therefore y_n = \frac{1}{14} \sqrt{\frac{12}{(600) \times (32)}} \approx (1.7) \quad 10^{-3} \text{ inches}$$

The output circuits of the Oculometer have a rise time of 20 milliseconds. Thus, approximately 10 individual millisecond samples of pupil noise will be averaged by the output channel. Thus the effective output pupil noise level will be

$$x_n \approx (0.47) \ 10^{-3} \text{ inches}$$

$$y_n \approx (0.63) \ 10^{-3} \text{ inches}$$

For the pupil diameter channel, a similar calculation applies:

$$\text{Total number of photoelectron/sample time} = \frac{300 \times 14}{32}$$

$$\therefore 14 \times (600) \, d_n = \sqrt{\frac{300 \times 14}{32}}$$

where d_n is the pupil radius noise in inches

$$\therefore d_n = \frac{1}{14} \sqrt{\frac{7}{32 \times 600}}$$

$$= 4.3 \times 10^{-3} \text{ inches}$$

Referred to the 20 millisecond rise time output channel

$\therefore d_n \approx 1.4 \quad x\ 10^{-3}$ inches.

For the corneal channel the noise calculation is as follows:

Total number of photoelectrons per sample time is

$600 + \frac{4.6}{2} 600 = 3.3 \quad 600 = 1980$

The corneal tracking noise ($x_{nn} = y_{nn}$) is given by

$184\ x_{nn}\ 600 = \sqrt{1980}$

$$\therefore \quad x_{nn} = \frac{\sqrt{1980}}{180\ 600}$$

$$\approx 4 \times 10^{-4} \text{ inches.}$$

After the 20 millisecond rise time filter:

$$x_{nn} = y_{nn} \approx 1.3 \times 10^{-4} \text{ inches.}$$

The total tracking noise of the Oculometer will be $X_n Y_n$ where

$$X_n = \sqrt{x_n^2 + X_{nn}^2}, Y_n = \sqrt{y_n^2 + y_{nn}^2}$$

$$= 0.49 \times 10^{-3} \text{ inches}, Y_n = 0.64 \times 10^{-3} \text{ inches.}$$

The Oculometer scale factor is approximately 3×10^{-3} inches per degree so that

$$x_n = 0.16^\circ \qquad y_n = 0.21^\circ$$

It may be noted that, in principle, the system could be operated as a corneal reflector tracker only by displacing the collection and illumination apertures (so that the pupil would appear dark) and locking-up the pupil-tracking channels. Under these conditions the noise calculation is as follow.

Total number of photoelectron per sample time

$$= 2.3 \ (600) = 1380$$

$$\therefore 184 \ x_{nn} \ 600 = \sqrt{1380}$$

$$\therefore x_{nn} = \frac{\sqrt{1380}}{184 \times (600)} = (3.4) \ 10^{-4} \text{ inches}$$

Applying the output smoothing correction

$$x'_{nn} = 1.1 \times 10^{-4} \text{ inches.}$$

Eye direction measurement by corneal reflection involves a scale factor of approximately 3.3×10^{-3} inches per degree.

$$\therefore x'_{nn} = 0.03 \text{ degrees.}$$

In appendix D the measured tube gain is given as 3×10^6. From this figure, and the current gain factors, it is possible to compute the value of V_{pw}, in volts, at the actual demodulator outputs.

In terms of image dissector output current:

$$V_{pw} = 3 \times 10^6 \times 600 \times 10^3 \times 1.6 \times 10^{-19} \text{ amps}$$
$$= 2.88 \times 10^{-7} \text{ amps}$$

The resistance of the preamplifier load is 50 KΩ, thus, in terms of A1 voltage output

$$V_{pw} = 14.4 \times 10^{-3} \text{ volts.}$$

The gain of A_2 = 5
A3/A4 = 1
A7 = 7 (pupil diameter)
A8 = 15(pupil x)
(A5/A6/A9) = 13(pupil y)
A10/A11 = 15(corneal position)

∴ For the pupil channel diameter $V_i = 35 \times 14 \times 10^{-3} \times 14$
$= 6.8$ volts/inch (of radius)

For the pupil channel x $V_i = 75 \times 14 \times 10^{-3} \times 15$
$= 15.8$ volts/inch

For the pupil channel y $V_i = 65 \times 14 \times 10^{-3} \times 15$
$= 13.7$ volts/inch

For the corneal position channels $V_i = 75 \times 184 \times 14 \times 10^{-3}$
$= 193$ volts/inch

(see Figure 21 for definition of V_i)

APPENDIX D

IMAGE DISSECTOR TESTS

Procedure

Remove image dissector assembly (IDA) from Oculometer. Measure output at output of preamplifier.

1. Measure dc output with Image Dissector high voltage off (VO)
2. Repeat with high voltage on, all lights off, and photocathode covered (VI). Perform this test at four points on photocathode.*
3. Set up a small test light about 30 in. from photocathode. Place the EG and G Light Mike close to the image dissector tube so that the lamp flux at the light mike detector is the same as at the photocathode. Measure image dissector output with lamp on (V3) and off (V4). Measure light mike output (on x 100 range) with light on (W_1) and off (W_2).
4. Measure dc output $(V5)_i$ and ac (rms) output $(V6)_i$ (using an RC LPF to limit bandwidth - record R and C but use values near $R = 10^4$, $C = 10^{-9}F$) (for i = 1,2,3). Record value (S) of image dissector load resistor.
5. Photograph uniformity of photocathode by displaying on x y scope.:

x: horizontal deflection voltage to image dissector

y: image dissector output filtered by 0.5 sec RC (NB x voltage should be changed slowly to avoid lag in the 0.5 sec RC).

Perform this test at about 9 values of the vertical image dissector deflection.

6. Photograph resolution (as above), at center and at 4 edge points of photocathode*, as aperture is made to move over a sharp black/white boundary.

---

* The point on the photocathode is selected by applying appropriate deflection signals to the x and y deflection coils.

Notation

V0 Output rms voltage with high voltage off

V1 Output dc voltage with high voltage off

V2 Output dc voltage with high voltage on, all lights out, photocathode covered.

V3 Output dc voltage with test light on.

V4 Output dc voltage with test light off.

W1 Light mike output (on x 100 range) with test light on.

W2 Light mike output (on x 100 range) with test light off.

$(V5)_i$ i =1, 2, 3 output dc voltage

$(V6)_i$ i=1, 2, 3 corresponding rms ac voltage

R,C Values of RC filter used to measure $(V6)_i$

S Image dissector output load resistor

Spectral Weighting Factors: Light mike: 0.82

S1: 0.52

Peak Light Mike Sensitivity: 7 mV/mW, detector area 1/14 cm^2

Image Dissector Aperture Area: $1.46 \times 10^{-3}\ cm^2$

A Tube gain
J Dark current
Z Tube sensitivity

To be calculated as specified below

Formulae

Tube Gain

$$V7 = 1/3 \left\{ \frac{(V_6)_1^2 - V_o^2}{(V_5)_1 - V_1} + \frac{(V_6)_2^2 - V_o^2}{(V_5)_2 - V_1} + \frac{(V_6)_3^2 - V_o^2}{(V_5)_3 - V_1} \right\}$$

$$\boxed{A = 1.25(V7)\frac{CR}{S}\ 10^{19}}$$

$$J = \frac{.07 \times 10^{-3}}{3.01 \times 10^{6} \times 5 \times 10^{4} \times 1.46 \times 10^{-3}} = 3.2 \times 10^{-13} \text{ amps/cm}^2$$

V3 - V4 = 217 ($\times 10^{-3}$) or 226.8 or 111.8

W1 - W2 = 74 ($\times 10^{-6}$) or 73 or 31.8

(Last set of values is rejected)

$$\therefore V/W = \frac{1}{2}\left(\frac{217}{74} + \frac{226.8}{73}\right) = 3.02 \cdot 10^{3}$$

$$\therefore \quad Z = \frac{8.03 \times 10^{4} \times 3.02 \times 10^{3}}{5 \times 10^{4} \times 3 \times 10^{6}} = 1.66 \times 10^{-3} \text{ amps/watt.}$$

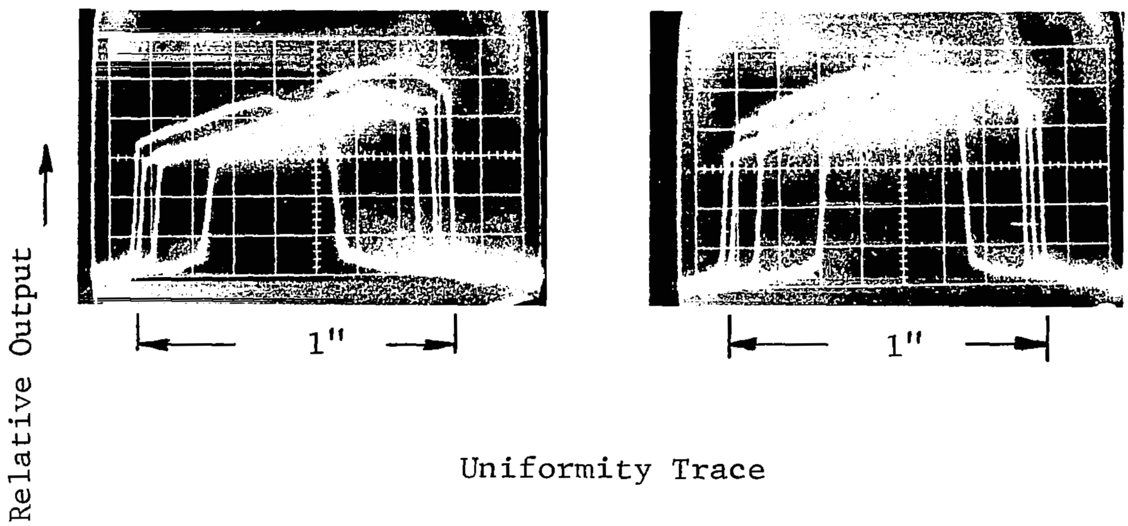
Photographs of uniformity plots and resolution plots of the tube are shown in Figure D.1.

APPENDIX E

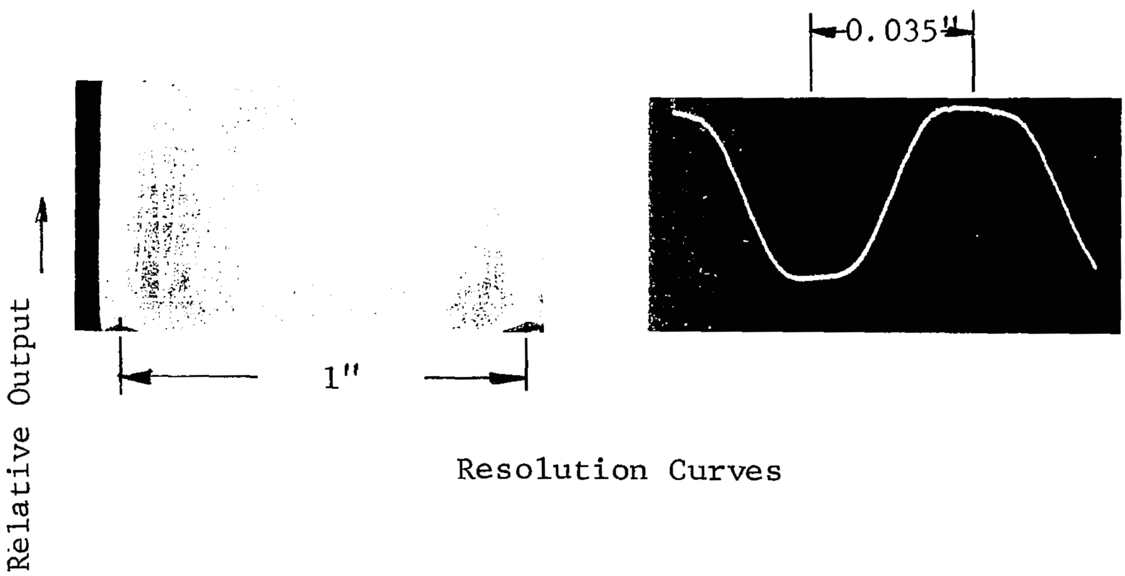
OPERATING AND ADJUSTMENT PROCEDURES

Normal Operating Instruction

1. Check that all 17 circuit cards are plugged in.
2. Check that all three plugs of the cable harness from the optomechanical unit are plugged into the sockets at the rear of the electronics rack.
3. Connect the x and y scan pattern outputs to the x and y plates of a CRT display. Maximum signal; plus or minus one volt.
4. Connect recording equipment as required.
5. Set the three switches at the bottom right of the electronics rack in the "off" position.
6. Plug in the line cord, and switch main power switch on.
7. Switch on high voltage and the lamp.



Uniformity Trace



Resolution Curves

Figure D.1

If the acquisition threshold controls have been set correctly, a coarse, unsynchronized, raster scan should be seen on the scan pattern scope. If the eye is placed at the eye space, the system should then acquire the eye and fall into the normal pupil, and corneal tracking scan witin about 0.1 seconds.

A. With a sheet of white diffusing paper held at the eye space, in place of the eye, there should be no interruptions (false acquisitions) of the pupil search raster.

B. Place the eye at the eye space and move the head so that the pupil scan goes to the edge of the scan pattern display. The system should lose track and revert to the pupil search mode. Test at all the edges of the scan pattern display.

C. When the eye is closed, the system should immediately lose track--the pupil scan should not drift off to the edge of the scan pattern display before initiation of the pupil raster.

D. Move the head away from the dichroic beam splitter (keeping the pupil scan pattern in the center of the scan display screen) for about 1 to 2 inches. The system should remain in pupil track, but lose corneal track. That is, a small corneal search raster should appear within the pupil area of the scan pattern. A cloud of small dots should be seen in this raster where the corneal tracking scan existed just before loss of corneal track. As the head is moved back within about an inch of its nominal position, the system should, in one clean step, revert back to the corneal track mode with the corneal tracking scan tracking the true corneal reflection (that is, not "hung up" on a false acquisition).

If the system passes these tests, it is ready for operation. If not, adjustment of the acquisition thresholds may be necessary.

Acquisition Threshold Adjustments

Pupil Acquisition: (Periodic Adjustment Only) This control is a trimpot mounted on the edge of card 8. Set the main pupil acquisition control (front panel knob) high enough to obtain a pupil raster as in test A above. With a piece of white paper held at the eye space, in place of the eye, turn the trimpot counter-clockwise until a cloud of false acquisitions is seen in the raster.

Turn the trimpot back (clockwise) until these false acquisitions just dissappear.

Pupil Loss (Routine Adjustment) This control is the main pupil acquisition control on the front panel. The control should be set to the minimum value consistent with satisfying tests B and C above.

Corneal Loss (Periodic Adjustment Only) (See Fig. E.1) This control is the trimpot mounted on the edge of card 7. It should be set to the most counter-clockwise position consistent with the system always reverting to a search mode when not tracking the true corneal reflection. (If it is turned too far in the counter-clockwise direction the corneal scan may drift about, but with the scan not tracking the reflection).

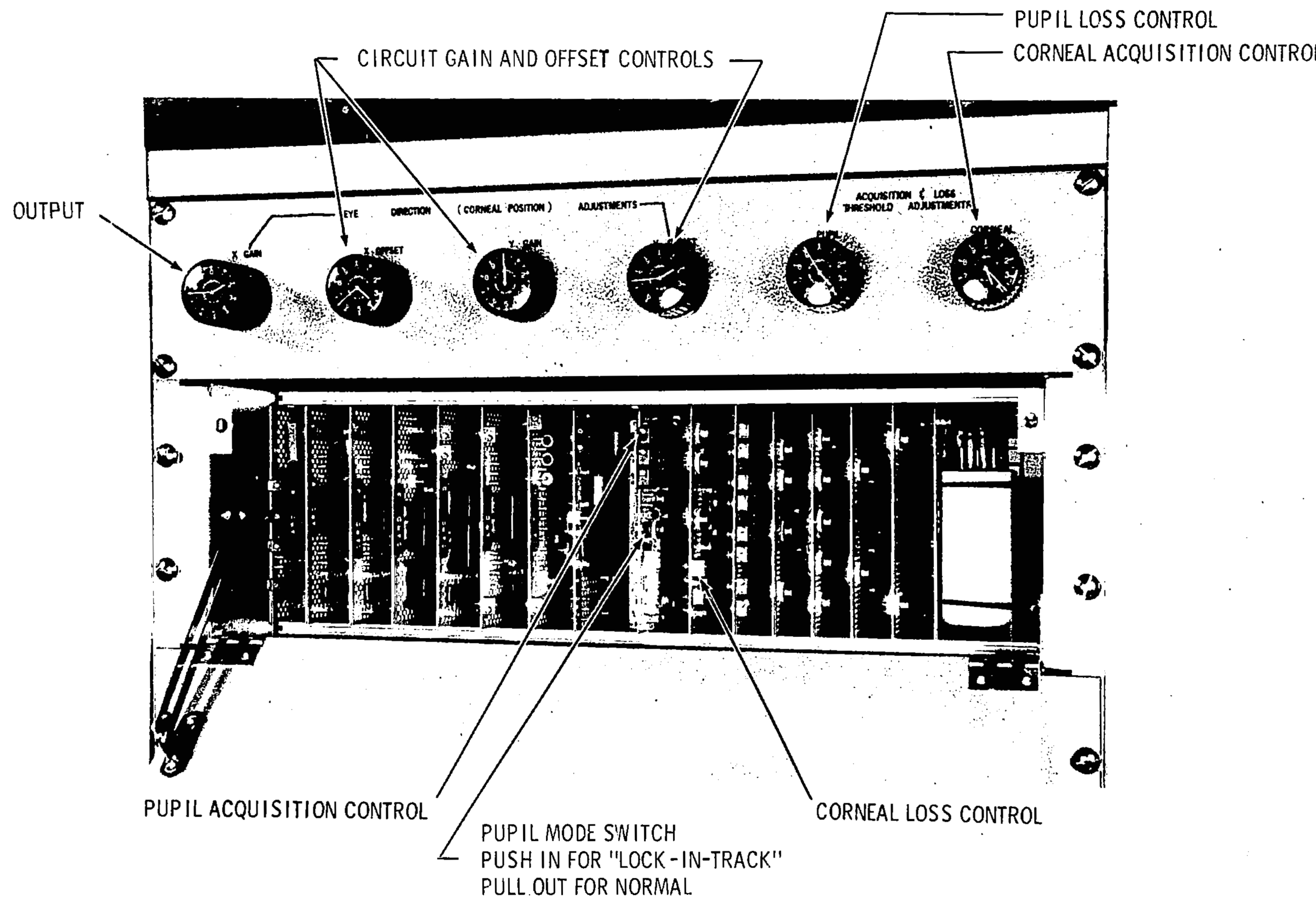


Figure E.1 FRONT PANEL

Corneal Acquisition (Routine Adjustment) This control is the main corneal acquisition control on the front panel. It should be set to the minimum value consistent with no false corneal acquisition.

Operational Notes

1. To minimize obscuration of the pupil area by the upper eyelid and eyelashes, the Oculometer should look up at the eye; that is, the red light of the Oculometer lamp should be seen by the operator towards the bottom of the visual field that it is desired to measure. This is accomplished by rotating the beam splitter.

2. In order to track the pupil with the correct diameter scan, the Oculometer incorporates an automatic pupil diameter tracking mechanism. Due to the details of this subsystem, it will be observed that when the corneal reflection enters the peak white sampling raster (present in the center of the pupil scan during normal tracking) the diameter of the pupil scan becomes somewhat smaller, returning to its original value as the reflection leaves this area. This idiosyncrasy doesn't interfere with tracking but its effect on pupil diameter information should be noted. For similar reasons, if the peak white sampling raster should not lie wholly within the pupil area, then the system will infer that the pupil is less bright than it actually is, and the pupil scan diameter will become

too large. (A false tracking mode can arise because of this effect if the pupil loss threshold is set too low. In this false mode, the pupil scan blows up to its maximum diameter and no corrective signal is generated because the peak white sampling raster is almost entirely off the true pupil.)

3. If the corneal reflection falls on, or near, the pupil boundary, then:

   a. The pupil scan diameter will be increased beyond the true value.
   b. The presence of the pupil boundary will interfere with corneal tracking.
   c. The presence of the corneal reflection will interfere with pupil tracking.

Thus, none of the Oculometer outputs can be relied upon when the corneal reflection is on, or near the pupil boundary. Effects (a) and (c) above will be particularly pronounced when the actual eye pupil diameter is very small. This is because the intensity of the pupil video is proportional to the square of the pupil diameter. The pupil video is, therefore, attenuated with a small pupil and pupil position and diameter tracking are then especially vulnerable to interference from the corneal reflection. Also, the corneal reflection will be more often near the boundary when the pupil is small.

4. The Oculometer measures the direction of the optical axis of the eye. The foveal axis of the eye is about 5 degrees away from this axis. The deviation of the foveal axis from the optical axis will give rise to errors associated with roll of the head. The magnitude is approximately one degree error in eye direction output for 10 degrees of head roll. The eyeball itself executes roll motion with large eye displacements. However, if this roll action is strictly in accordance with Listing's Law, then the effect will not be an error but an additional nonlinearity in the relationship between eye direction output and the actual direction of the eye.

Numerical Data

Diameter of ID Tube Aperture at Eye	0.02 in.
Diameter of eye space	1.2 in.
Diameter of 3 mm pupil	0.12 in.
Approximate size of peak white sampling raster at eye	0.08 in. x 0.08 in.
Diameter of corneal reflection when sharply focused at eye	0.0027 in.
Oculometer scale factor (relative displacement of corneal reflection per degree)	about 0.003 in per degree of eye motion

Electronic scale factor:

At scan pattern output	about 1 volt/in.
Pupil position output	10 volts/in.
Pupil diameter	about 6 volts per in.

Corneal integrators (pins 10 and 11 on card 12)	100 volts/in.
Time Constant of RC filter on eye direction circuits	about 20 ms
Output noise level	approximately 0.3° rms
Maximum error with head motion	±0.5°
Speed of Acquisition	approximately 0.2 seconds
Tracking Rates	Will follow x direction eye motions of 20° executed at the maximum eye slewing rates.

OCULOMETER SERVICE ADJUSTMENTS

Focus The image dissector focus control should be set to the position as determined below:

1) Lock system into pupil search (with finger switch on card 8.)
2) Short-circuit pupil position (x) output.
3) Place a set of diffusely illuminated horizontal grating bars (about .05 in. wide) in the eye space.
4) Switch off Oculometer lamp
5) Connect the video output to the y channel of a CRT and pupil y position output to the x channel of this CRT.
6) The CRT should show a line of video with breaks in it corresponding to the grating bars. Adjust Oculometer focus control for maximum rise time and minimum signal in the black bar segments of this video display.

<u>Pupil Balance</u> Observe the scan pattern output on a CRT display such that the peak white sampling raster fills about 1/3 of the screen. Note the position of the corneal reflection relative to this raster. Constrict the pupil of the eye by changing the ambient illumination of the other eye. Adjust the pupil position balance controls (the x control is the pot within card 10, near the top, the y control is the pot within card 11) so that there is no displacement of the corneal reflection as the eye pupil diameter changes.

Adjust the pupil diameter balance control (the pot within card 10 near the center) so that the pupil scan expands out sharply to its proper value on going into pupil track (e.g., after a blink.) The two limits are:

a) The scan expands too vigorously and sometimes the circular scan "blows up"
b) The scan is very slow to expand out to its proper diameter and is noisy, particularly when the corneal reflection is within the sampling raster.

<u>Corneal Balance</u> These controls are within card 12. They should be adjusted so that when the system is tracking the eye, with the head several inches away from the correct position, there is no tendency for the corneal scan to drift off in any particular direction. (i.e., no bias)

Fault Guide Lines

1) Pupil system satisfactory but corneal acquisition system cannot be adjusted to give reliable tracking. Check Focus Control.

2) Pupil scan diameter "blows up", or is noisy, or is too small, or the system will not operate in normal ambient light. Check Pupil Diameter Balance and Pupil Position Balance.

REFERENCES

1. The Oculometer, by John Merchant, Honeywell Inc., Boston, Mass., July 1967, NASA CR-805.

2. The Eye, edited by Hugh Davson, Academic Press, New York, 1962. Vol. 3, pp. 16, 17.

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NEW TECHNOLOGY APPENDIX

"After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made."

NASA-Langley, 1969 —— 5 CR-1422